Forward Neutrinos from Charm at the LHC and Prompt Neutrinos at IceCube

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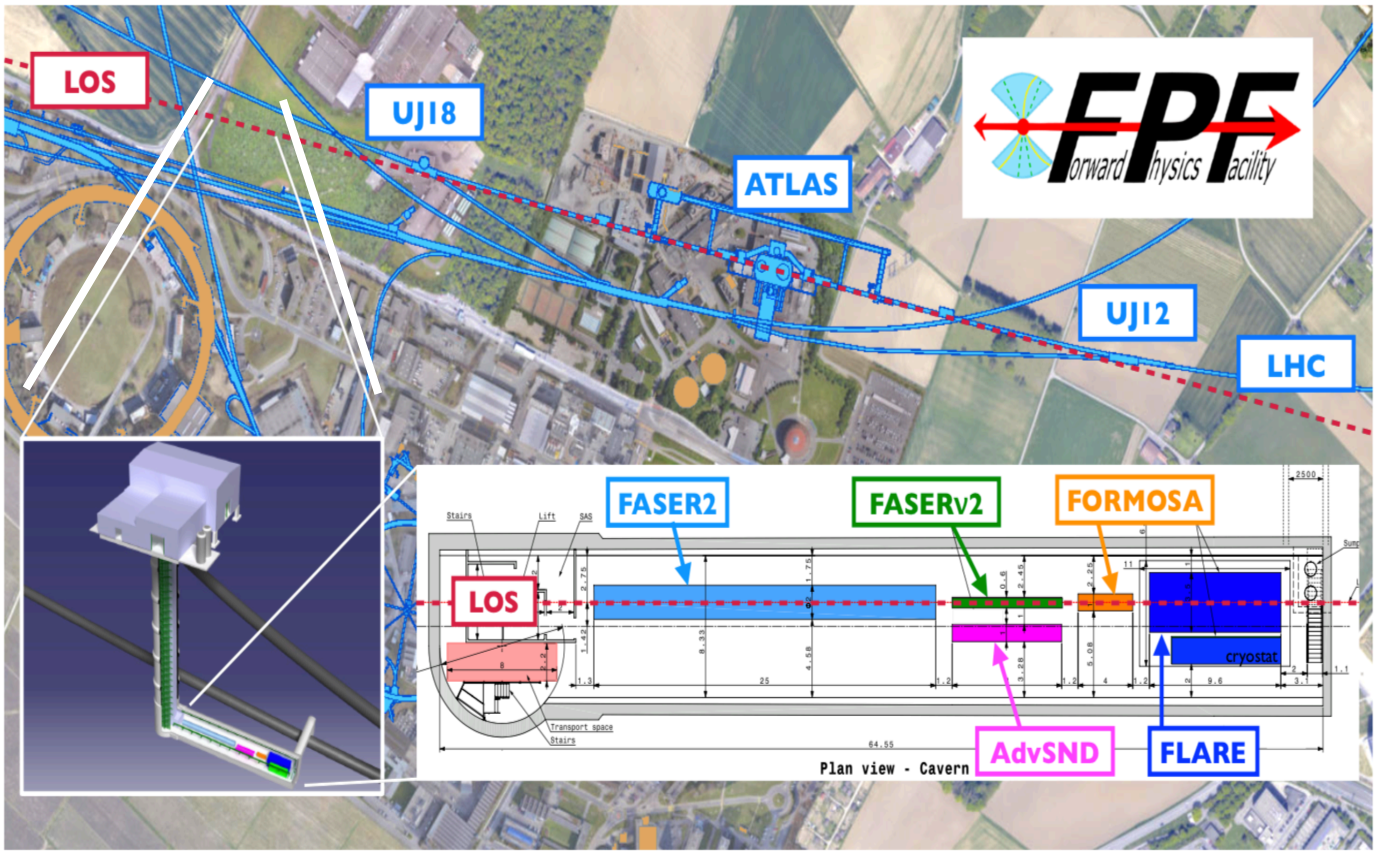
in collaboration with Atri Bhattacharya, Felix Kling and Anna Stasto

See also FPF Papers: arXiv:2203.05090 and Anchordoqui et al. Phys. Rept. 968 (2022) 1

The Forward Physics Facility

The Forward Physics Facility (FPF) is a proposal to create a cavern with the space and infrastructure to support a suite of far-forward experiments at the Large Hadron Collider during the High Luminosity era.

FPF experiments will detect about 1M neutrino interactions (1K tau neutrinos) with neutrino energies up to a few TeV



Need the facility infrastructure and detectors designed for Standard Model and BSM Physics.

FPF White Papers: arXiv:2203.05090 ("long paper"), see also Anchordoqui et al. Phys. Rept. 968 (2022) 1

Forward rapidity regions for detectors

Detector			
Name	Mass	Coverage	Luminosity
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}

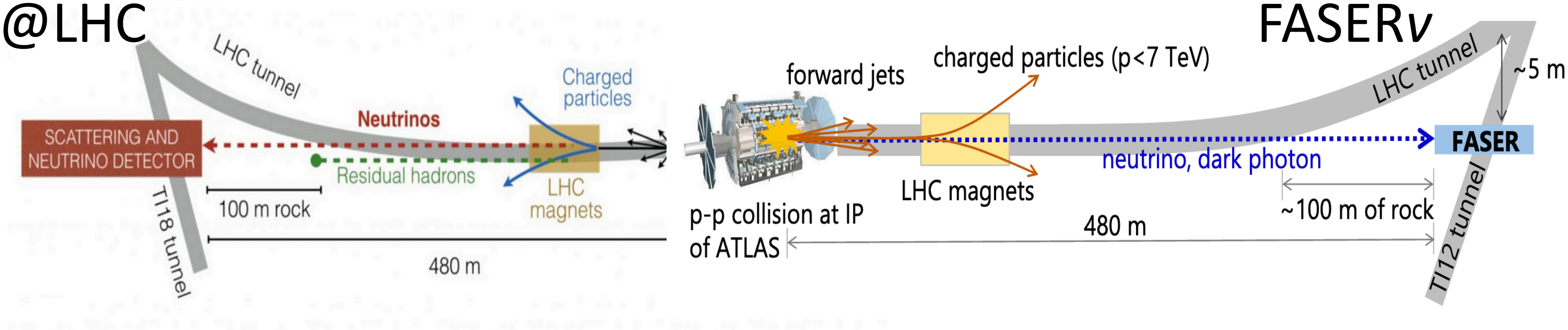
Run 3

FASERν and SND@LHC detectors are installed

AdvSND ("near") in range

SND@LHC

FASERν



The Physics at FPF

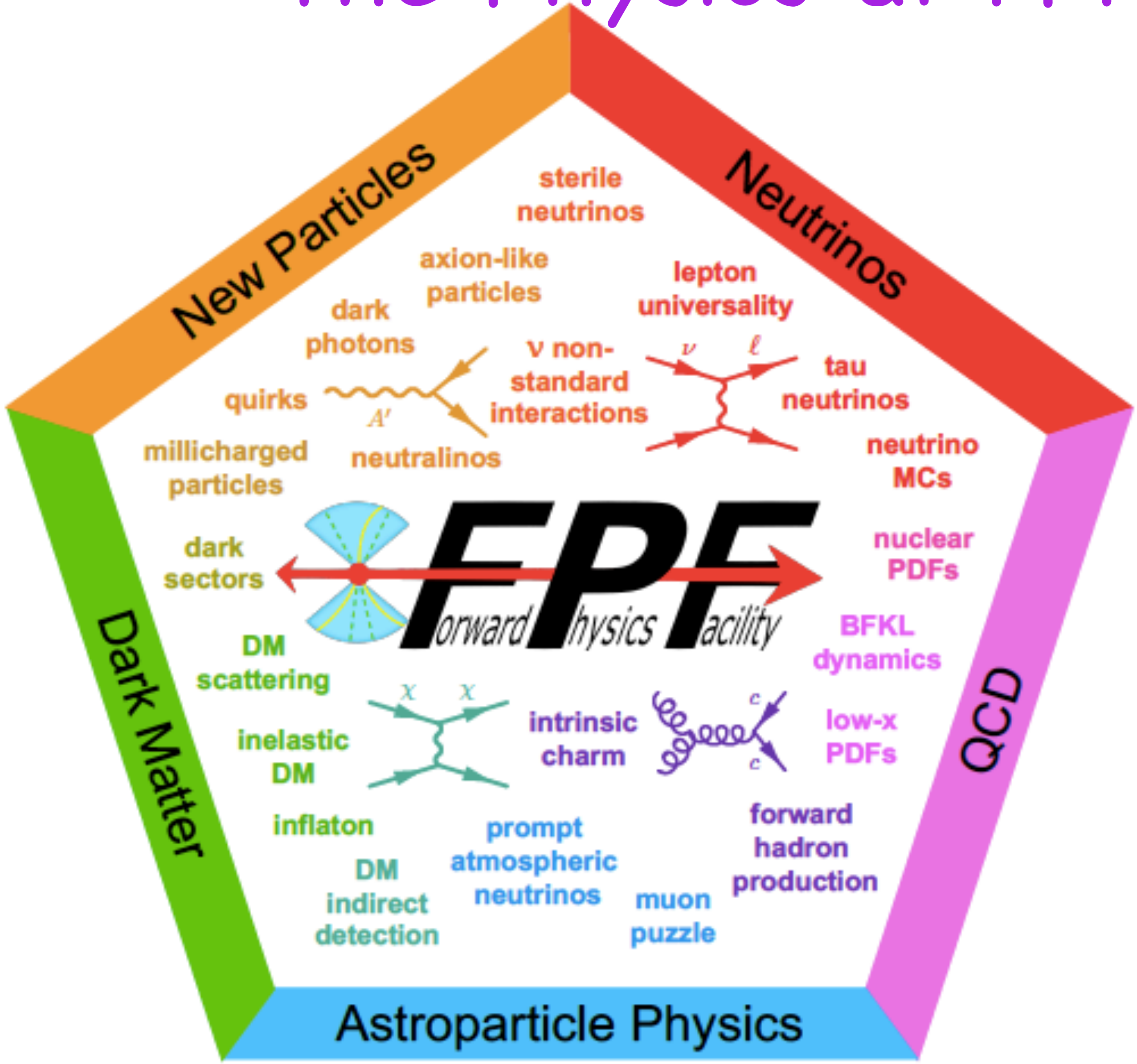


Figure 2: The Forward Physics Facility will probe topics that span multiple frontiers, including new particles, neutrinos, dark matter, QCD, and astroparticle physics.

Production of Neutrinos

At LHC (forward detectors: FASERnu …):

p + p → pions, kaons, D-mesons .. → neutrinos

Energy of protons 14TeV (LHC beam)

Atmospheric neutrinos:

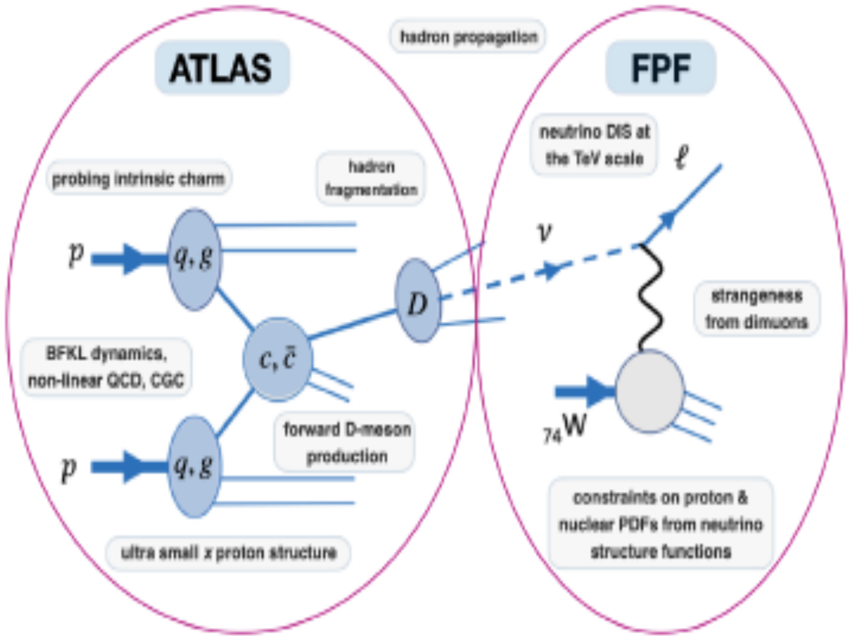
p + Air (p) → pions, kaons, D-mesons →neutrinos

Folding comic ray proton spectrum with the production

Astrophysical neutrinos (from AGNs, GRB..)

p + p and p+ gamma, folding with the proton energy spectrum

QCD (neutrino production)

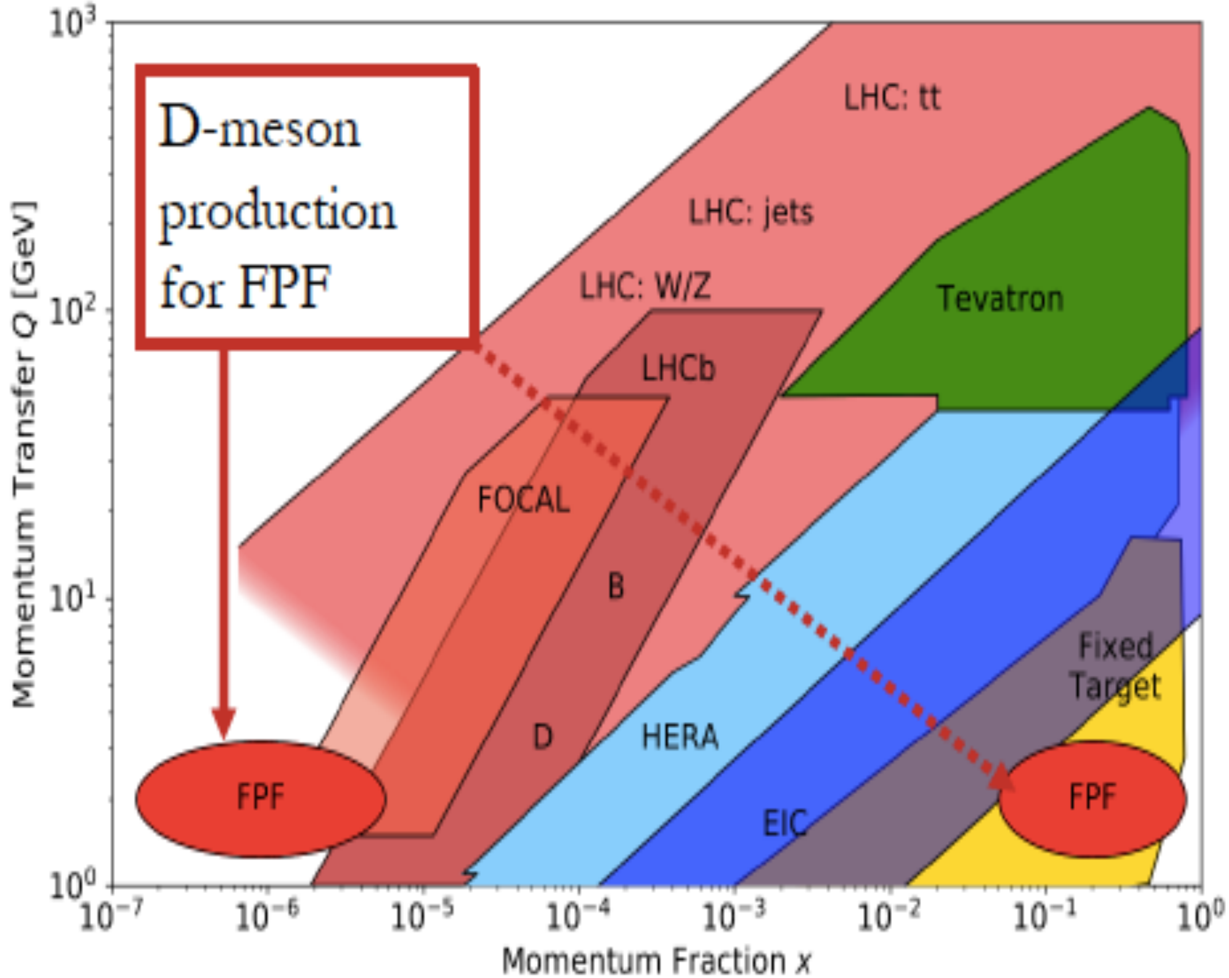


Forward neutrino production is a probe of forward hadron production, BFKL dynamics, PDFs at ultra small x (10^-7) and small Q^2

Important implications for high energy neutrino experiments

New kinematic regimes.

forward charm: high rapidity, $x_1 \gg x_2$ in gluon PDF



Charm Production in NLO pQCD using PDFs

The total charm cross section in pQCD is given by:

$$\sigma(pp \to c\bar{c}X) = \int dx_1 dx_2 G(x_1, \mu^2) G(x_2, \mu^2) \hat{\sigma}_{gg \to c\bar{c}}(x_1 x_2 s)$$

and differential charm cross section

$$\frac{d\sigma}{dx_F} = \int \frac{dM^2_{c\bar{c}}}{(x_1 + x_2)s} \sigma_{gg \to c\bar{c}}(\hat{s}) G(x_1, \mu^2) G(x_2, \mu^2)$$

where

$x_1,\ x_2:$

$$x_F = x_1 - x_2$$

$$x_F \simeq x_E = E/E'$$

$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}}{s}} \pm x_F\right)$$

$$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1$$

$$E \sim 10^7 \text{ GeV} \to x_2 \sim 10^{-6}$$

$$x_{1,2} \sim m_c / 2 m_p E_\nu$$

For high energies we need gluon PDF for small x, and low Q^2

FONLL program: Cacciari, Greco and Nason, JHEP 05 (1998) 007; Cacciari, Frixione, Nason, JHEP 03 (2001) 006

Calculated in pQCD by matching the Fixed Order NLO terms with NLL high p_T resummation

Charm Production in k_T Factorization Approach

$$\frac{d\sigma}{dx_F}(s, m_Q^2) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} dz\,\delta(zx_1 - x_F)x_1 g(x_1, M_F) \int \frac{dk_T^2}{k_T^2}\hat{\sigma}^{\mathrm{off}}(z, \hat{s}, k_T) f(x_2, k_T^2)$$

x_F is the Feynman variable for the produced heavy quark
$x_1 g(x_1, M_F)$ is the integrated gluon density on the projectile side, $\hat{\sigma}^{\mathrm{off}}(z, \hat{s}, k_T)$ is the partonic cross section for the process $gg^* \to Q\bar{Q}$, where g^* is the off-shell gluon on the target side, and $f(x_2, k_T^2)$ is the unintegrated gluon density.

For the unintegrated gluon density, we have used the resummed version of the BFKL evolution which includes important subleading effects due to DGLAP evolution

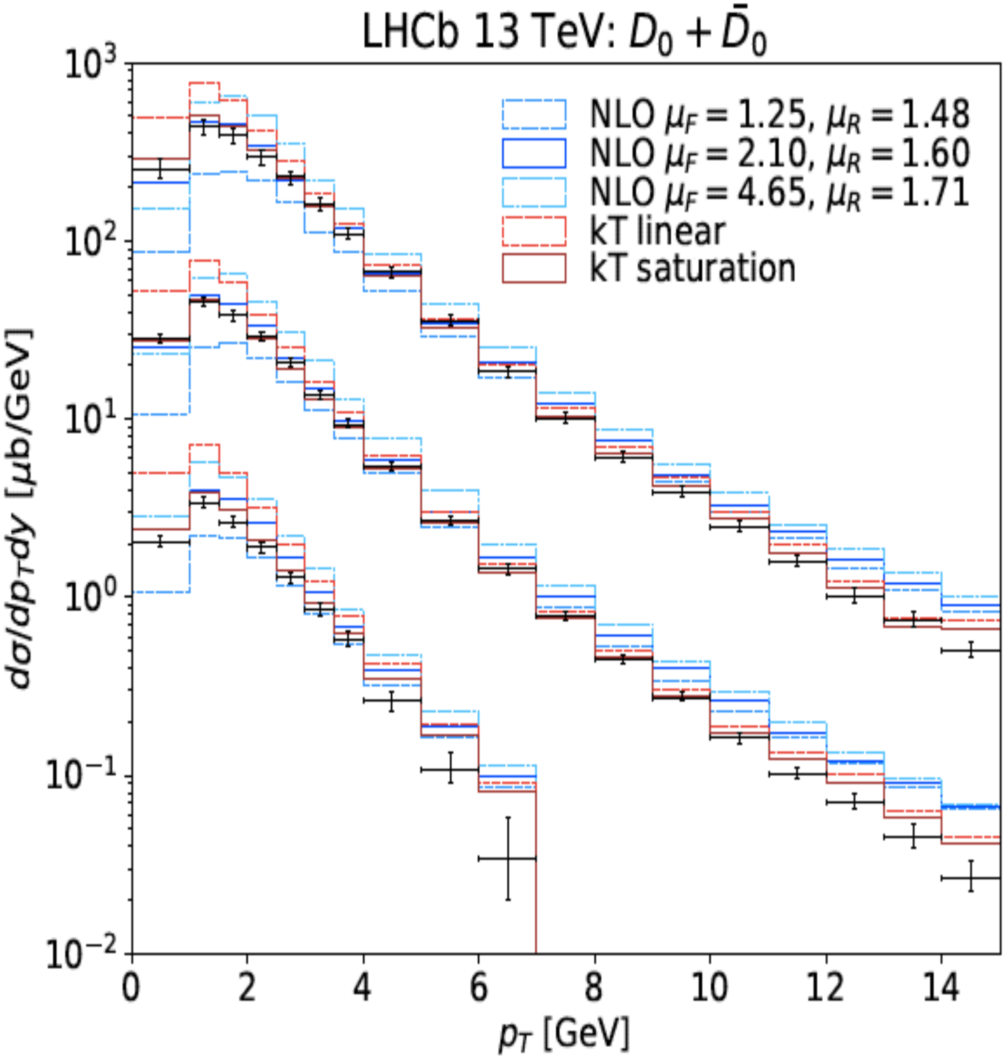
Theoretical uncertainties

Parton distribution functions at small x and small Q^2 (mostly gluons, unconstrained by HERA data), Factorization and Renomalization scale, charm quark mass, Fragmentation function

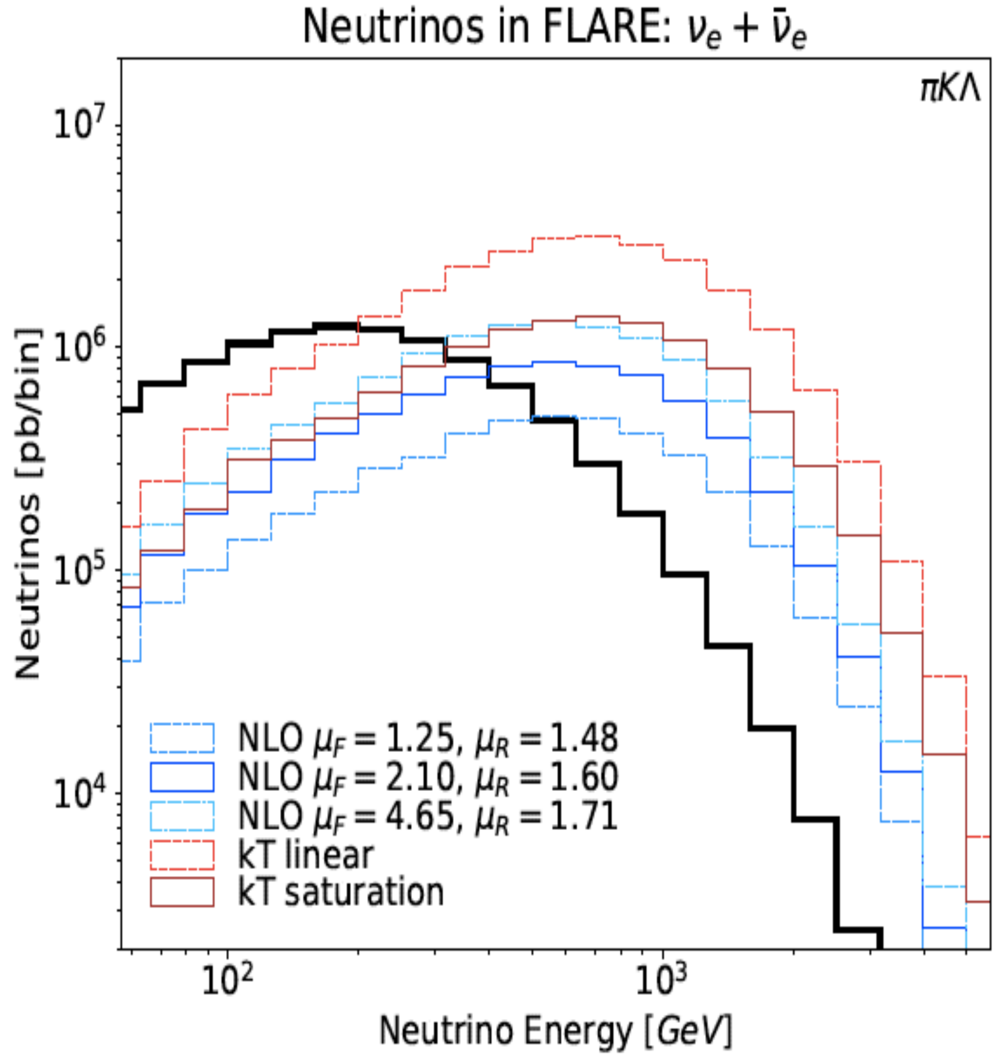
We use LHCb and ALICE data in different rapidity regions and at several energies to reduce theoretical uncertainties (LHCb data covers rapidity up to 4.5)

k_T factorization approach depends on gluon distribution at large-x, charm quark mass

D-meson production at LHCb in different rapidity regions

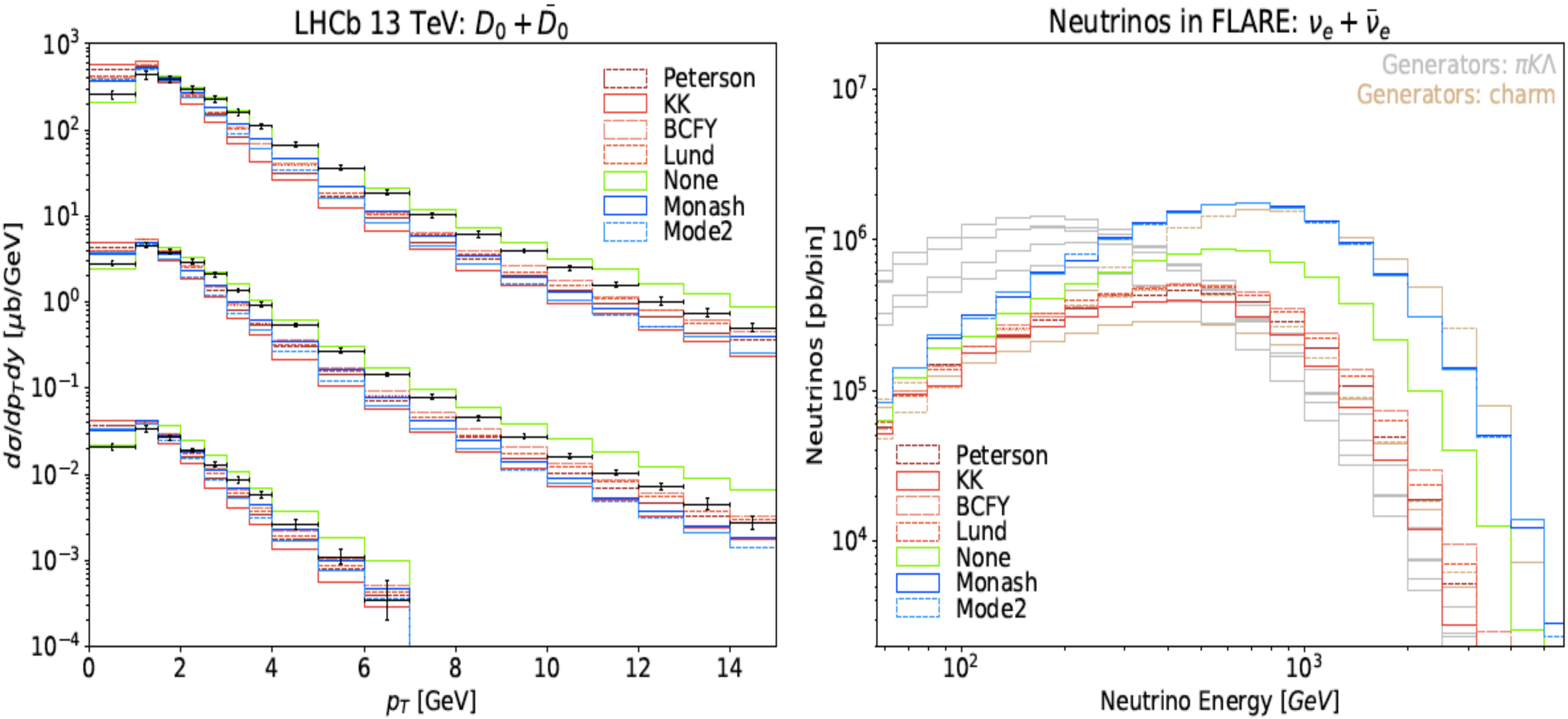


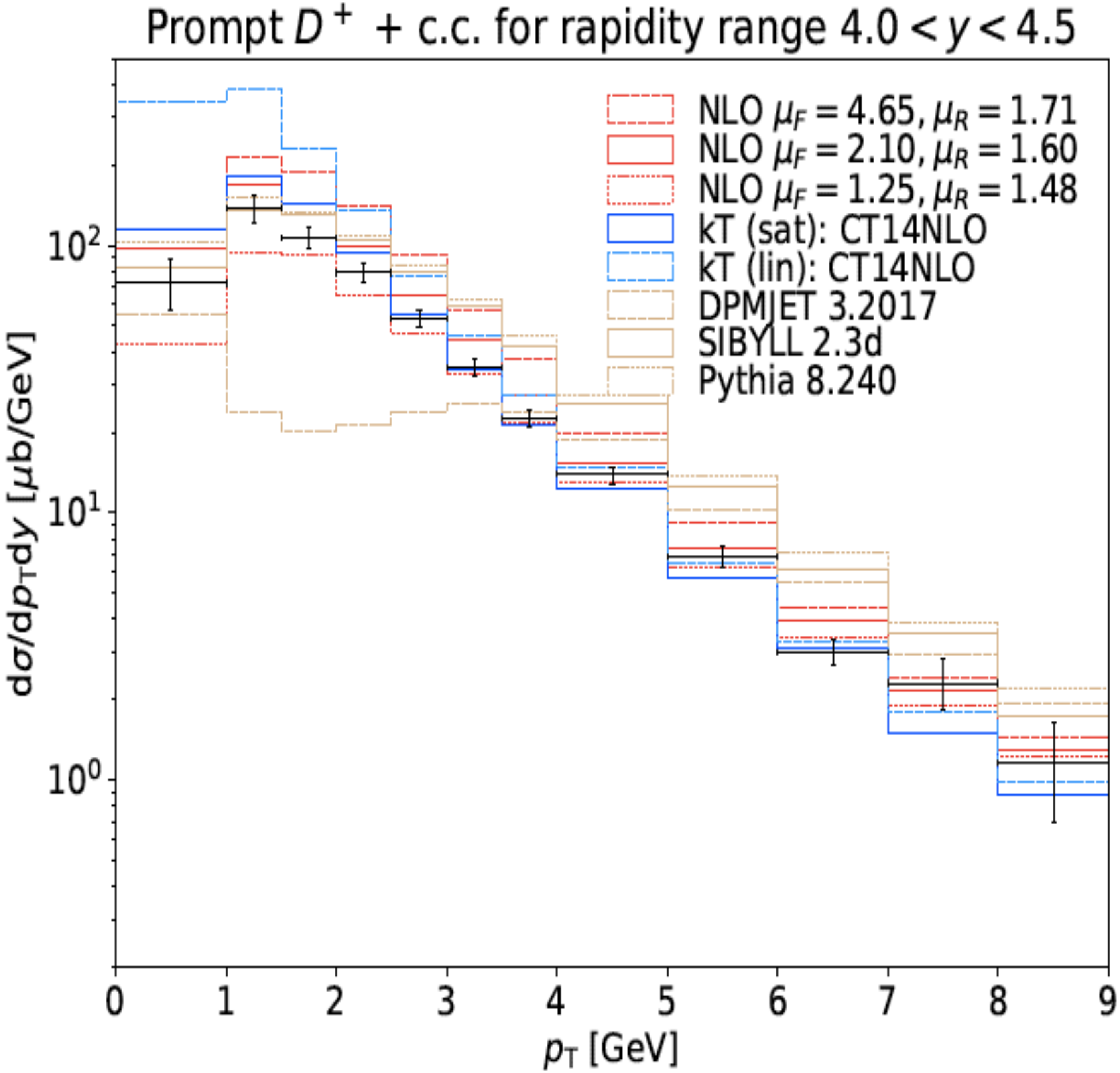
Neutrinos from D-meson decays



Neutrinos with energy above 300GeV come predominantly from charm.

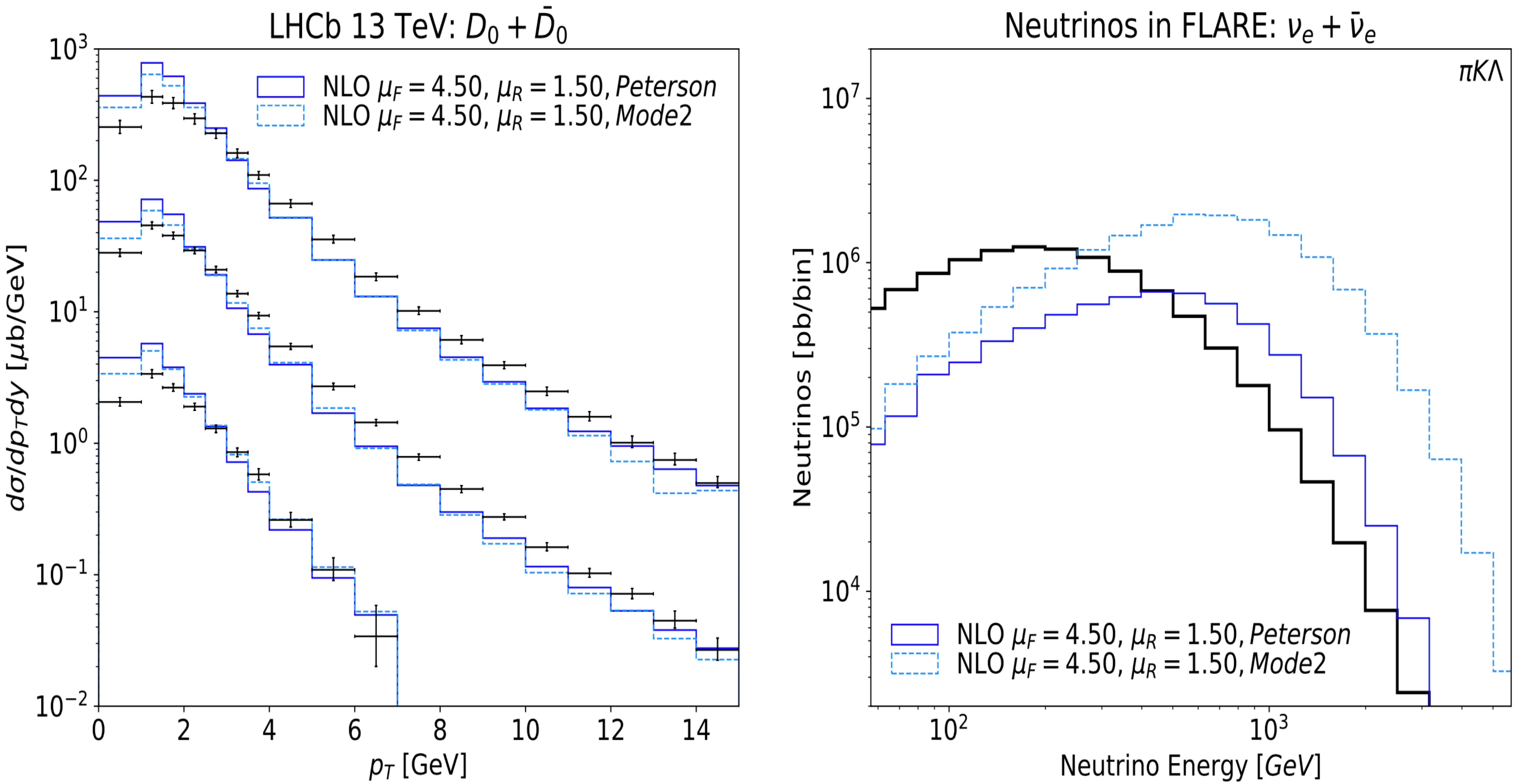
Fragmentation Functions





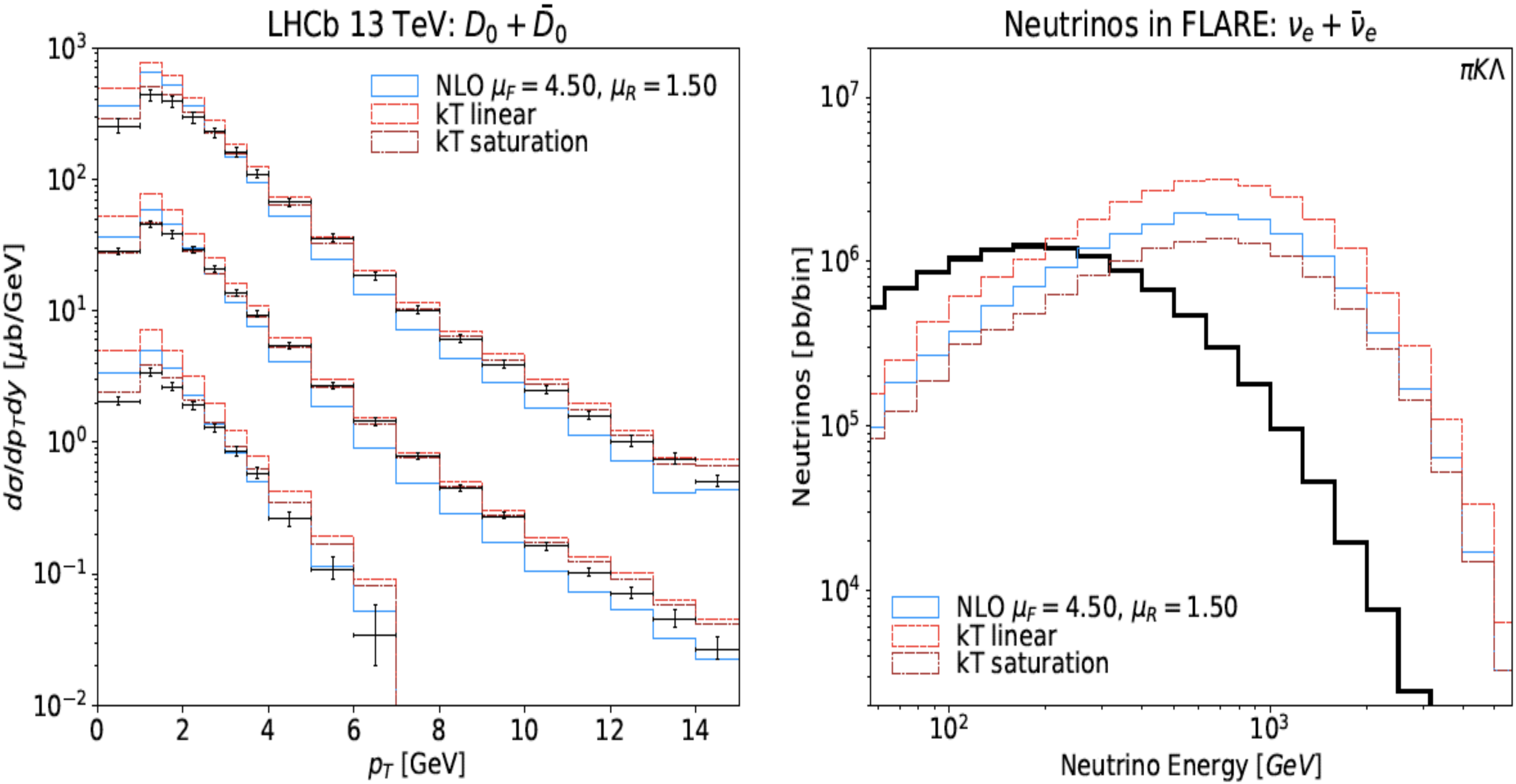
Prompt D^+ + c.c. for rapidity range $4.0 < y < 4.5$
NLO $\mu_F = 4.65, \mu_R = 1.71$
NLO $\mu_F = 2.10, \mu_R = 1.60$
NLO $\mu_F = 1.25, \mu_R = 1.48$
kT (sat): CT14NLO
kT (lin): CT14NLO
DPMJET 3.2017
SIBYLL 2.3d
Pythia 8.240
$d\sigma/dp_T dy$ [μb/GeV]
p_T [GeV]

NLO with different fragmentation functions

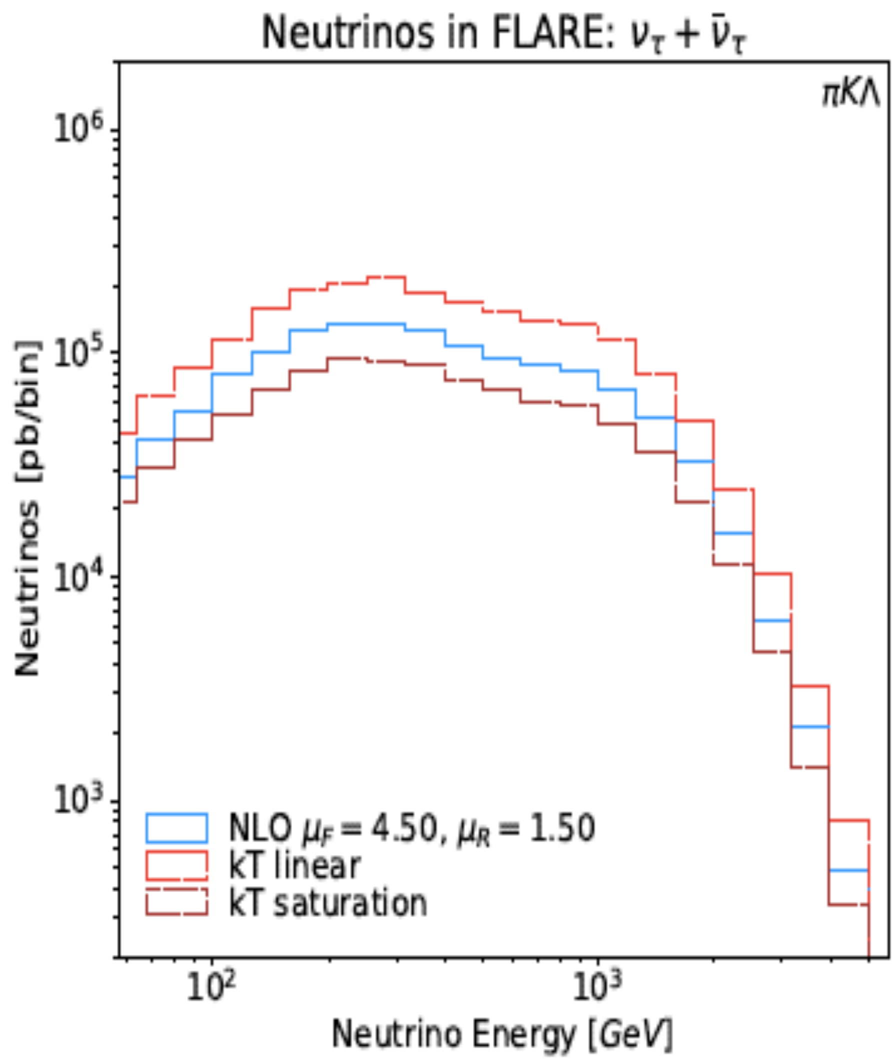


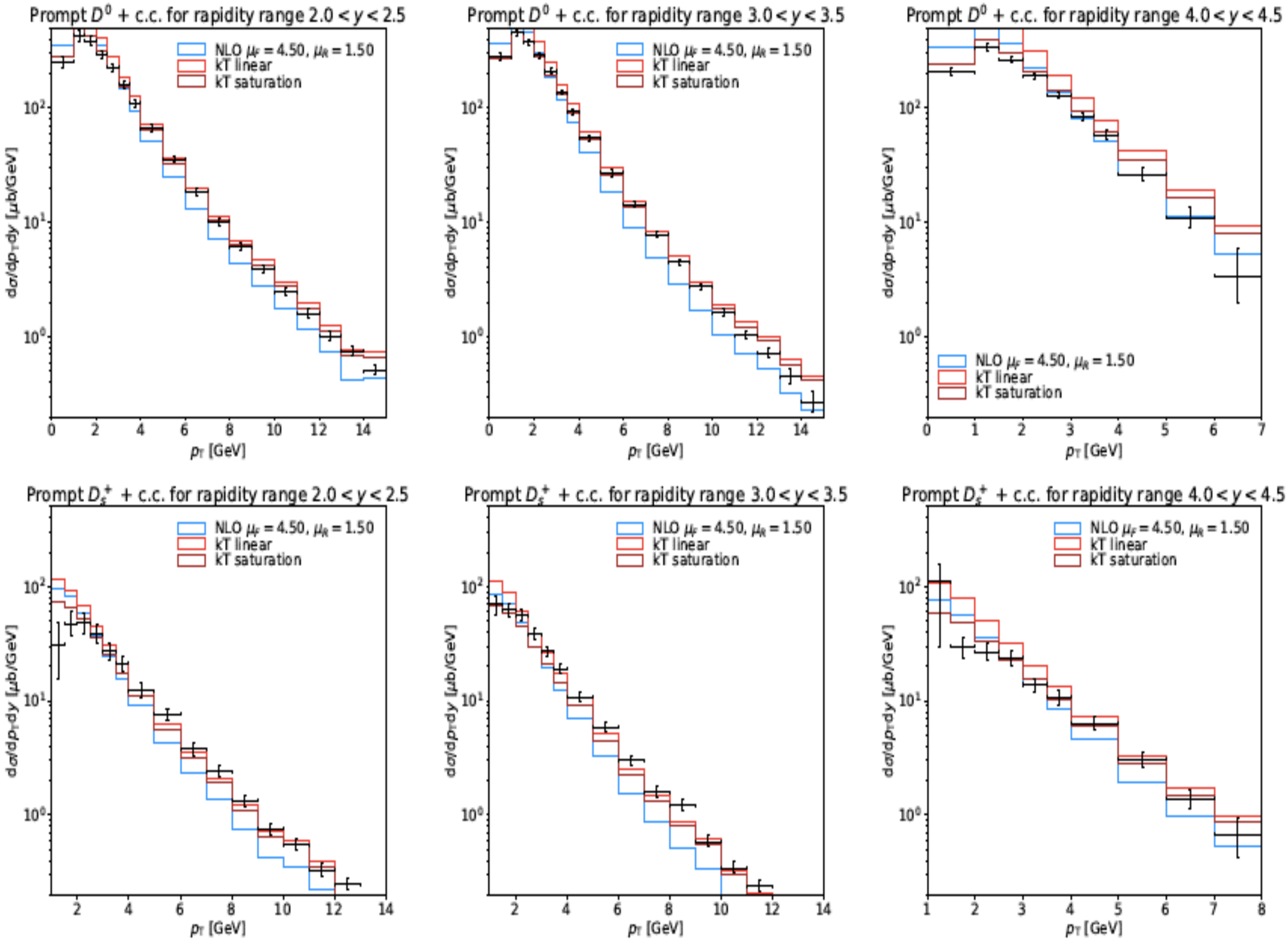
Similar results for LHCb but very different neutrino flux in FLARE

NLO and kT distributions at LHCb and neutrino fluxes at FASER (Peterson Fragmentation function)

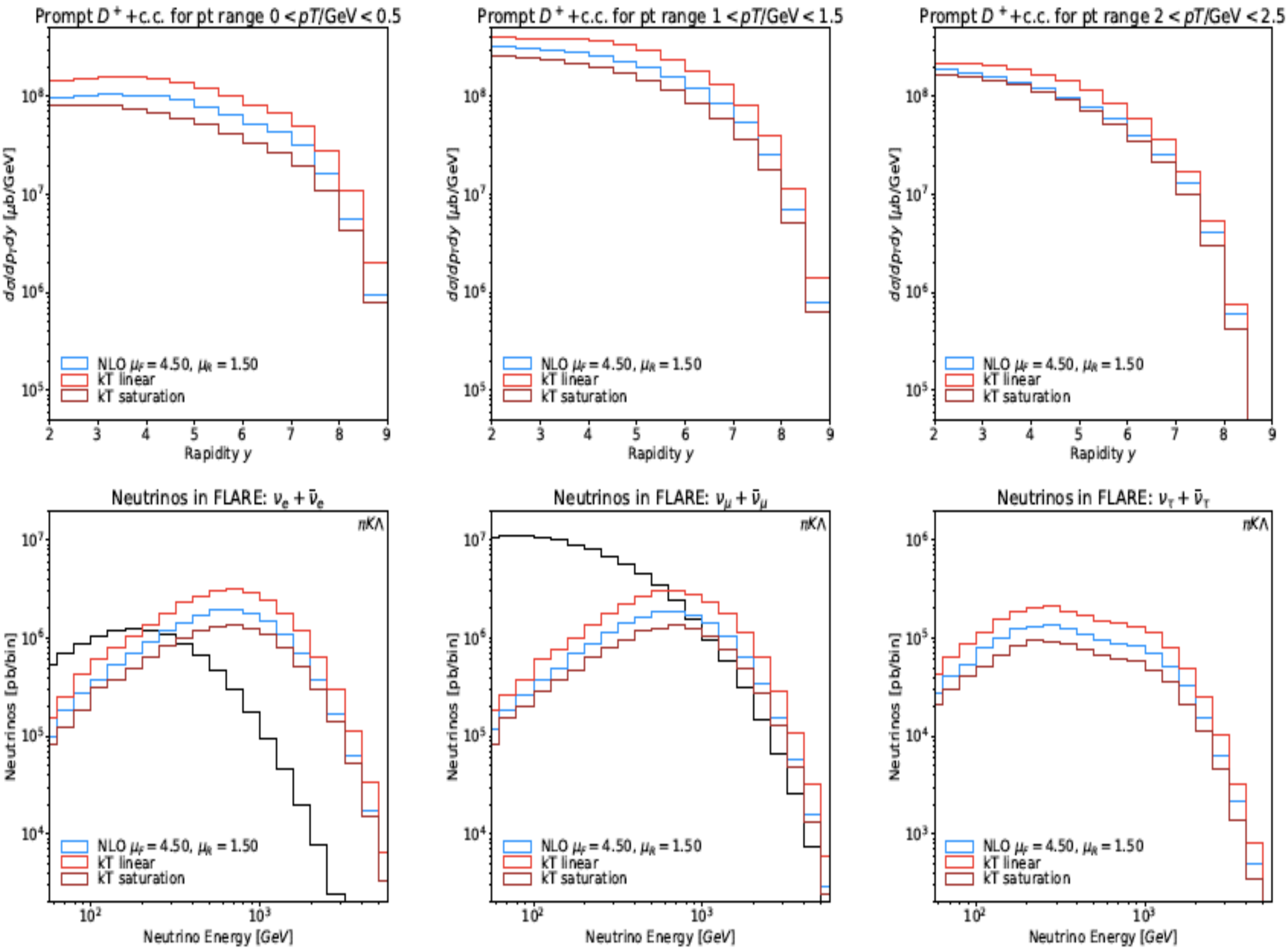


Tau neutrino flux from charm



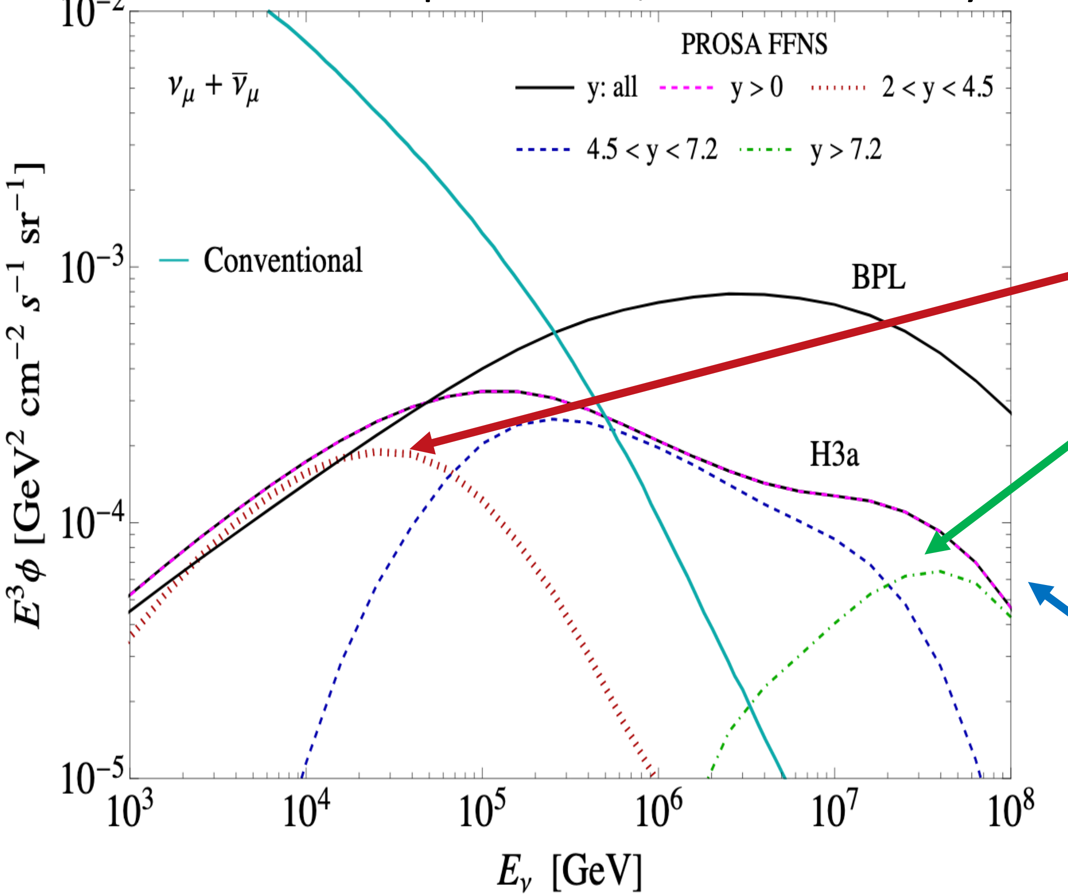


Prompt D^0 + c.c. for rapidity range $2.0 < y < 2.5$
Prompt D^0 + c.c. for rapidity range $3.0 < y < 3.5$
Prompt D^0 + c.c. for rapidity range $4.0 < y < 4.5$
Prompt D_s^+ + c.c. for rapidity range $2.0 < y < 2.5$
Prompt D_s^+ + c.c. for rapidity range $3.0 < y < 3.5$
Prompt D_s^+ + c.c. for rapidity range $4.0 < y < 4.5$
NLO $\mu_F = 4.50$, $\mu_R = 1.50$
kT linear
kT saturation
$d\sigma/dp_T dy$ [μb/GeV]
p_T [GeV]


Prompt D^++c.c. for pt range $0 < pT/\mathrm{GeV} < 0.5$
Prompt D^++c.c. for pt range $1 < pT/\mathrm{GeV} < 1.5$
Prompt D^++c.c. for pt range $2 < pT/\mathrm{GeV} < 2.5$
$d\sigma/dp_T dy$ [μb/GeV]
Rapidity y
NLO $\mu_F = 4.50$, $\mu_R = 1.50$
kT linear
kT saturation
Neutrinos in FLARE: $\nu_e + \bar{\nu}_e$
Neutrinos in FLARE: $\nu_\mu + \bar{\nu}_\mu$
Neutrinos in FLARE: $\nu_\tau + \bar{\nu}_\tau$
$\pi K \Lambda$
Neutrinos [pb/bin]
Neutrino Energy [GeV]

Astroparticle physics connections – prompt atmospheric neutrinos

BPL=broken power law; H3a=cosmic ray flux



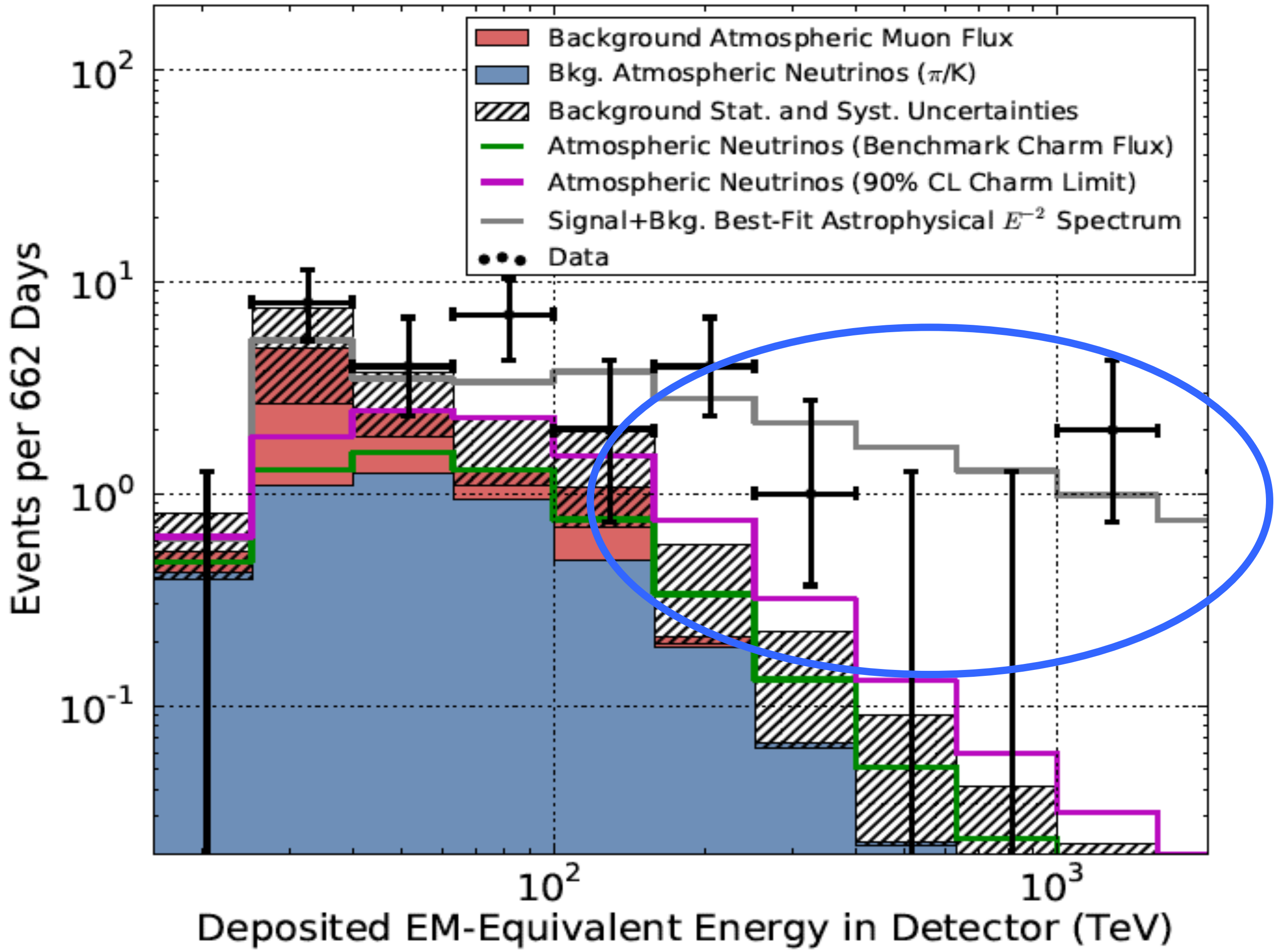
Prompt neutrinos are a background to astrophysical neutrinos

LHCb

FPF

charm production and decay "prompt atmospheric neutrinos"

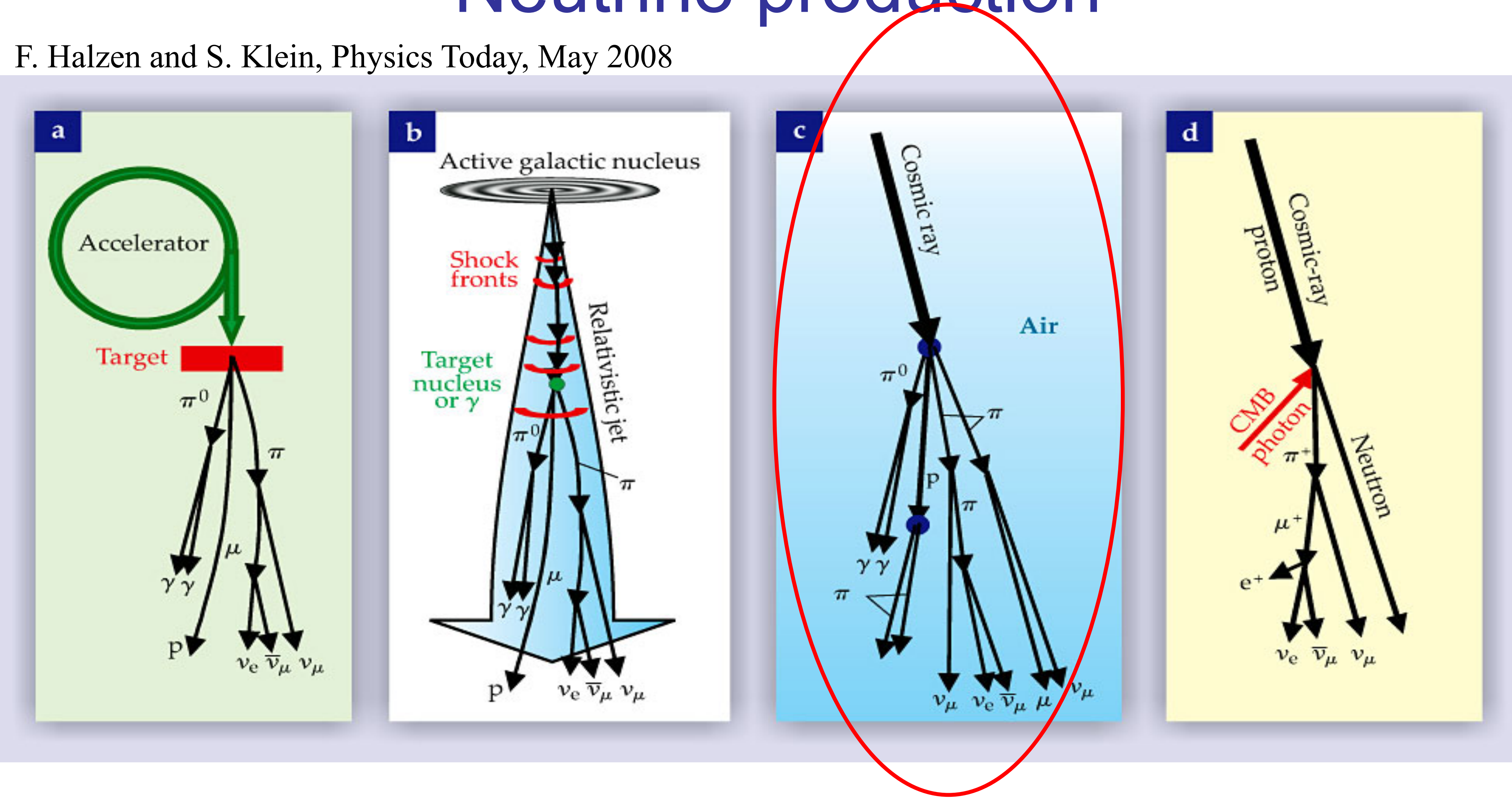
Atmospheric Neutrinos are the Main Background



IceCube, Science 342 (2013), arXiv:1311.5238

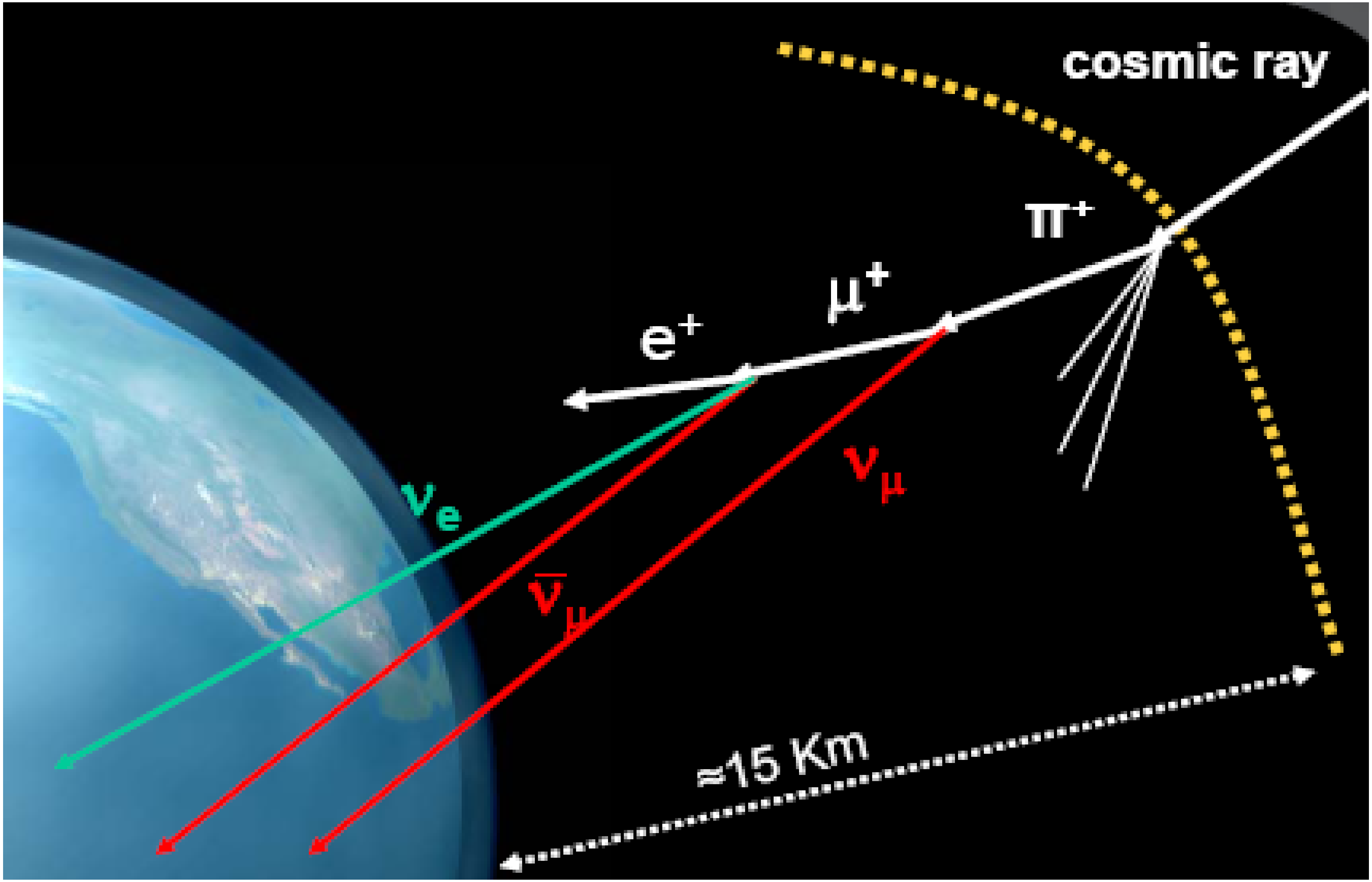
Neutrino production

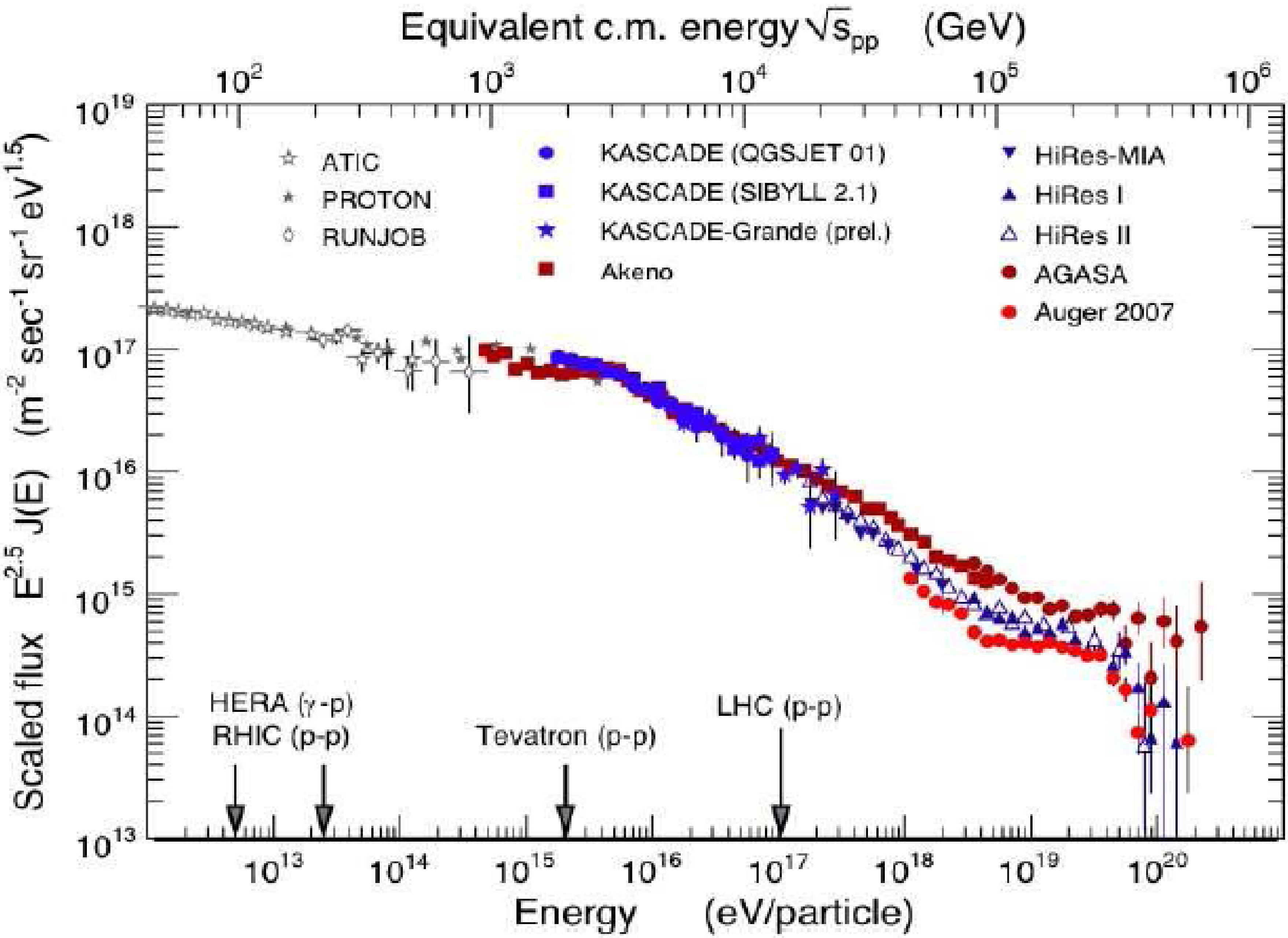
F. Halzen and S. Klein, Physics Today, May 2008



Same production mechanism for accelerator beams, inside astrophysical objects, in the atmosphere, and for the cosmogenic neutrino flux.

Cosmic Rays




Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)
10^2
10^3
10^4
10^5
10^6
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Auger 2007
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

Prompt neutrino flux

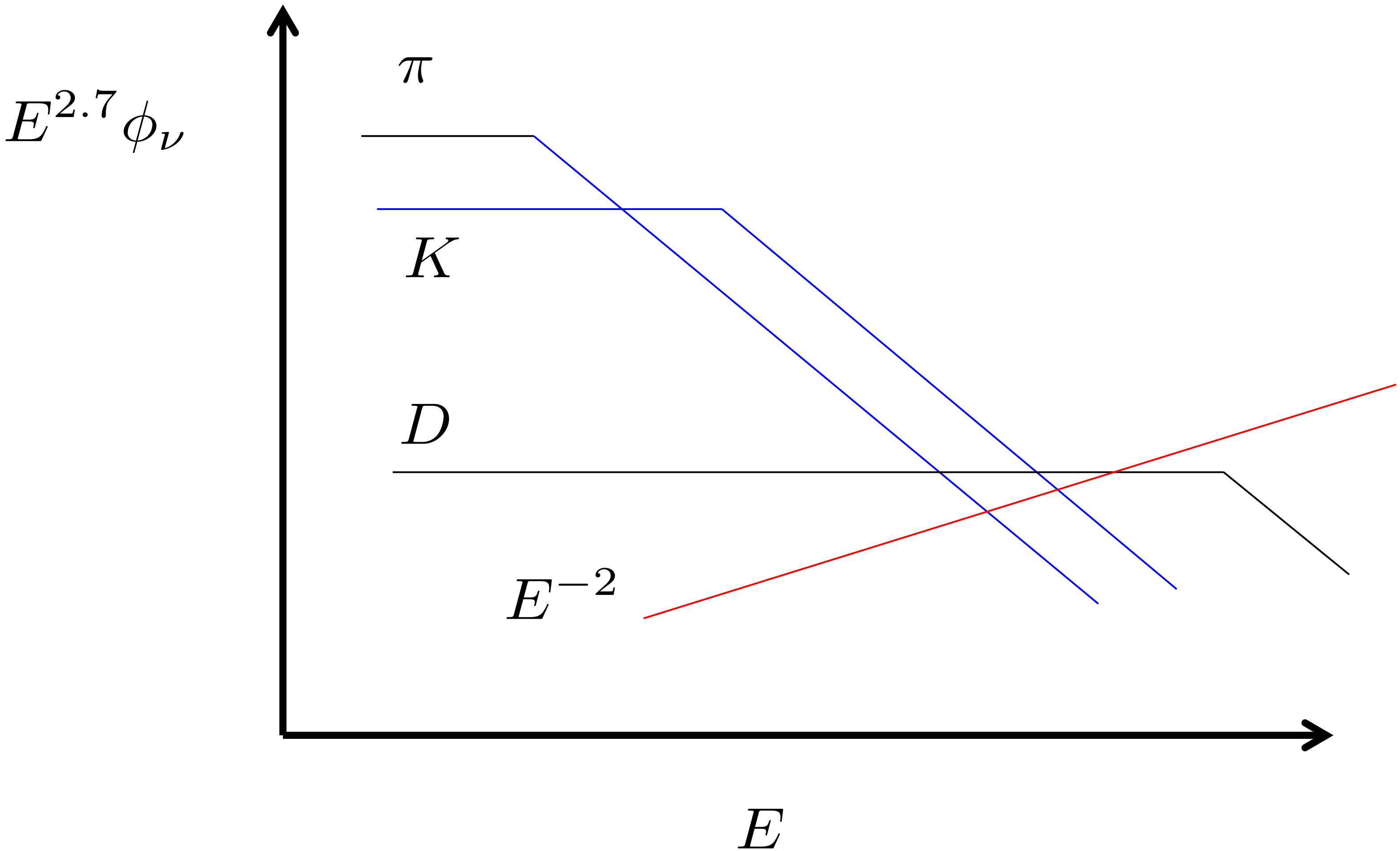
- Hadrons containing heavy quarks *(charm or bottom)* are extremely short-lived:
  ⇒ decay before losing much energy
  ⇒ neutrino energy spectrum is harder

- However, production cross-section is much smaller

- There is a cross-over energy above which prompt neutrinos dominate over the conventional flux

- This is called the atmospheric *prompt neutrino flux*

Schematically



Transport equations for evaluating atmospheric neutrino flux

- To find the neutrino flux we must solve a set of cascad
equations given the incoming proton flux:

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \to NY)$$

$$\frac{d\phi_M}{dX} = S(NA \to MY) - \frac{\phi_M}{\rho d_M(E)} - \frac{\phi_M}{\lambda_M} + S(MA \to MY)$$

$$\frac{d\phi_\ell}{dX} = \sum_M S(M \to \ell Y)$$

- X is the slant depth: "amount of atmosphere"
ρd_M is the decay length, with ρ the density of air
λ_M is the interaction length for hadronic energy loss

Z-moments

- We solve the transport equations by introducing Z-moments:

$$Z_{kh} = \int_E^\infty dE' \frac{\phi_k(E',X,\theta)}{\phi_k(E,X,\theta)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(kA \to hY; E', E)}{dE}$$

- Then

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\rho d_M} - \frac{\phi_M}{\lambda_M} + Z_{MM}\frac{\phi_M}{\lambda_M} + Z_{NM}\frac{\phi_N}{\lambda_N}$$

- Solve equations separately in low- and high-energy regimes where attenuation is dominated by decay and energy loss, respectively, and interpolate

Particle production

The particle physics inputs are the energy distributions for production and decay:

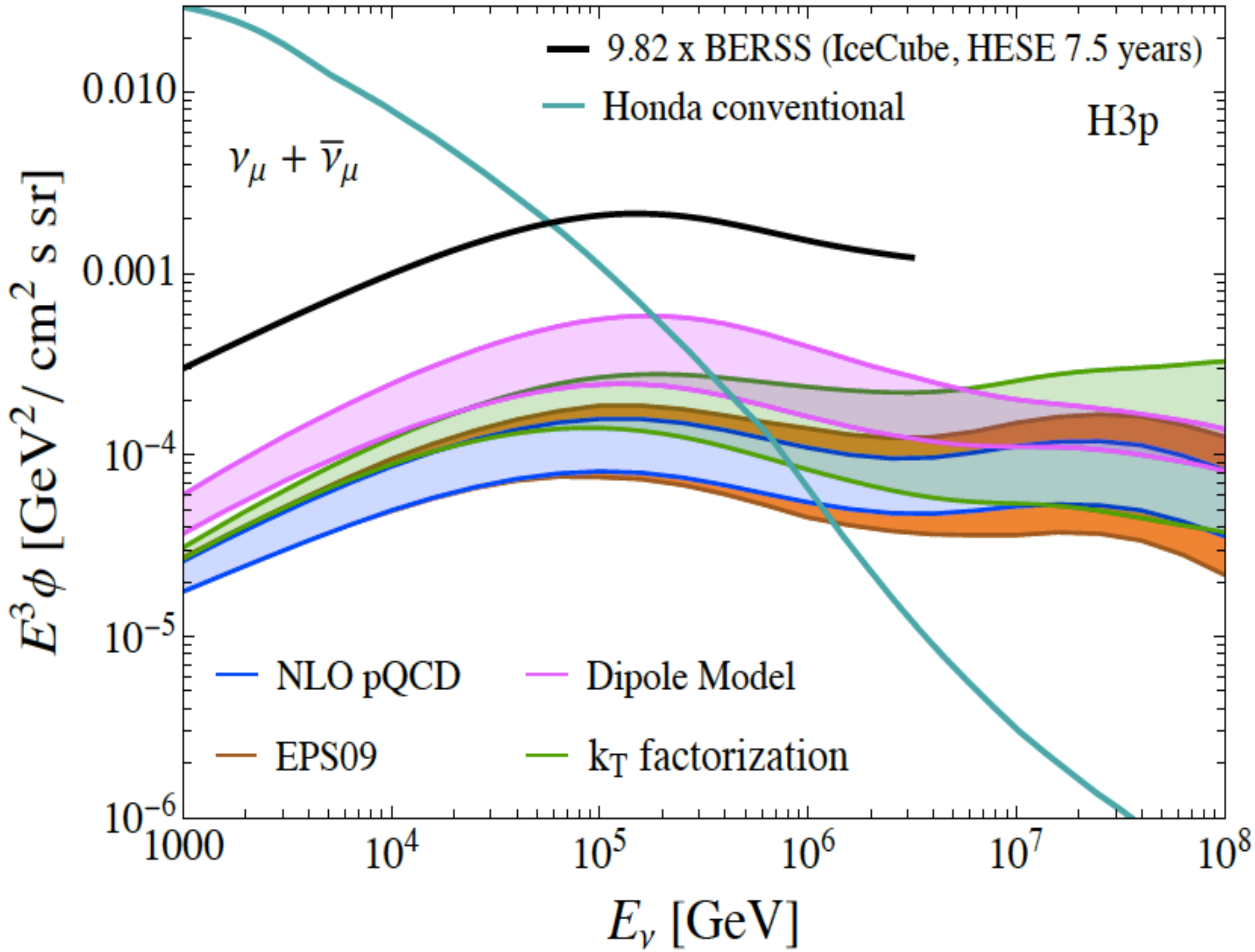
$$\frac{dn(k \to j; E_k, E_j)}{dE_j} = \frac{1}{\sigma_{kA}(E_k)} \frac{d\sigma(kA \to jY, E_k, E_j)}{dE_j}$$

$$\frac{dn(k \to j; E_k, E_j)}{dE_j} = \frac{1}{\Gamma_k} \frac{d\Gamma(k \to jY; E_j)}{dE_j}$$

along with the interaction lengths, or cooling lengths

$$\lambda_N(E) = \frac{\rho(h)}{\sigma_{NA}(E) n_A(h)}$$

Prompt Neutrino Flux



A. Bhattacharya, R. Enberg, Y.S. Jeon, M.H. Reno, I. Sarcevic and A. Stasto, JHEP 11 (2016) 167

Conclusion

High energy muon and electron neutrinos and all of tau neutrinos produced in the forward region, come from the decay of charmed mesons. Forward neutrinos are probe of QCD at small x and small Q^2.

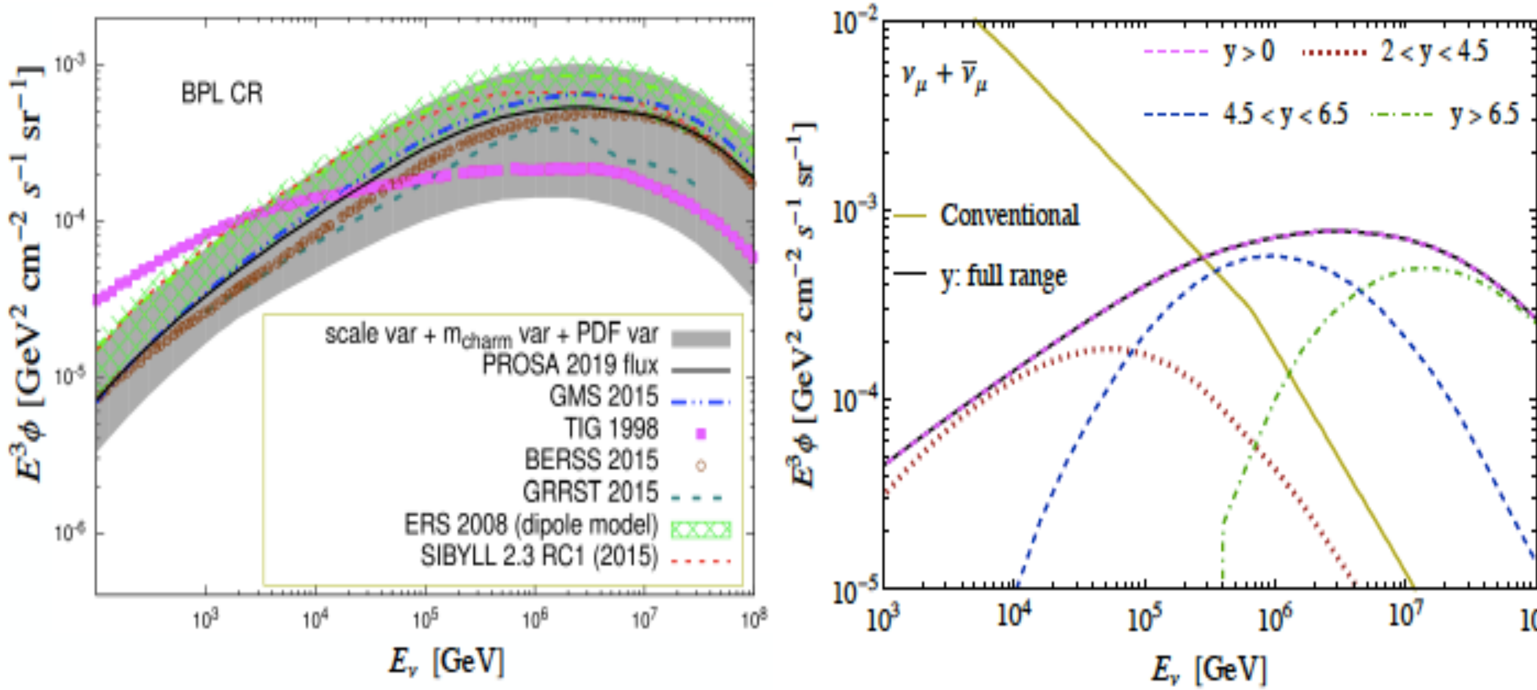
We use fits to LHCb data to constraint QCD parameters. FASER will probe different kinematic region, providing information about importance of non-linear effects and saturation that is relevant in the forward region

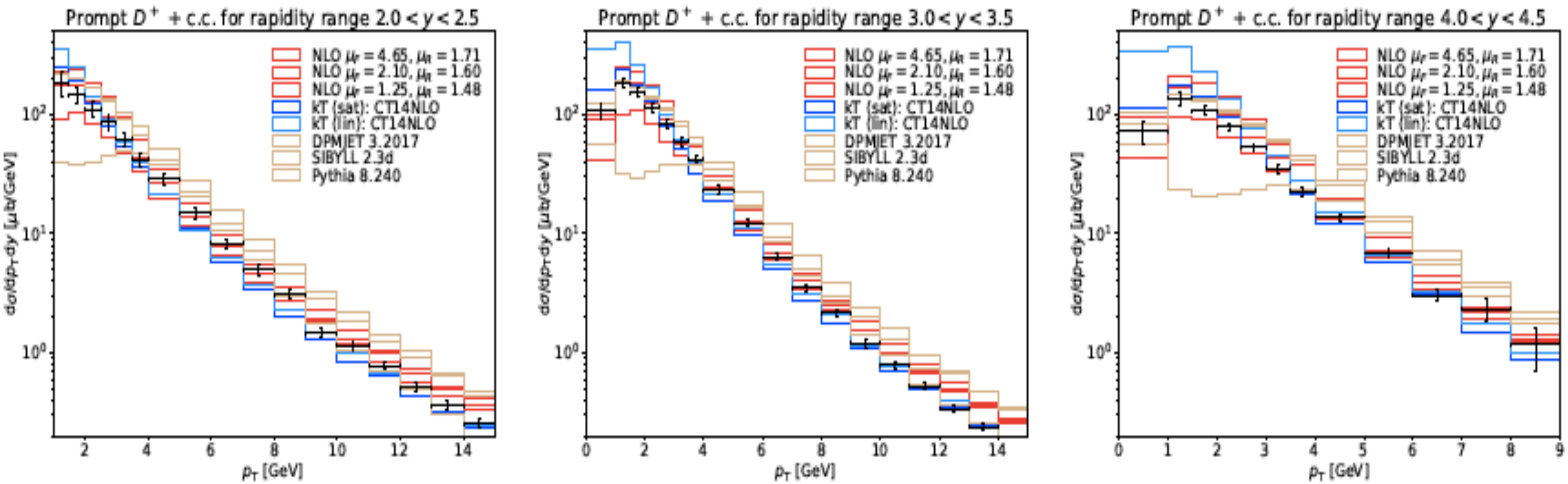
Prompt atmospheric neutrino flux has the same QCD input, but it is folded with the cosmic ray flux. Connection to forward neutrino production at the HL-LHC, i.e. measurements with FASER can reduce theoretical uncertainties in the prediction of the prompt neutrino flux

It is important to pursue Forward Physics Facility Program at HL-LHC and Neutrinos telescopes such as IceCube-Gen2, km3Net.. Study correlations between these experiments, as well as multimessengers (gamma rays, cosmic rays, etc)

Backup Slides

Experiments The FPF is uniquely suited to exploit physics opportunities in the far-forward region, because it will house a diverse set of experiments, each optimized for particular physics goals. The envisioned experiments and their physics targets are shown in Fig. 2. FASER2, a magnetic spectrometer and tracker, will search for light and weakly-interacting states, including long-lived particles, new force carriers, axion-like particles, light neutralinos, and dark sector particles. FASERν2 and Advanced SND, proposed emulsion and electronic detectors, respectively, will detect $\sim 10^6$ neutrinos and anti-neutrinos at TeV energies, including $\sim 10^3$ tau neutrinos, the least well-understood of all known particles. FLArE, a proposed 10-tonne-scale noble liquid detector, will detect neutrinos and also search for light dark matter. And FORMOSA, a detector composed of scintillating bars, will provide world-leading sensitivity to millicharged particles and other very weakly-interacting particles across a large range of masses.


BPL CR
$E^3\phi$ [GeV^2 cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]
scale var + m$_{charm}$ var + PDF var
PROSA 2019 flux
GMS 2015
TIG 1998
BERSS 2015
GRRST 2015
ERS 2008 (dipole model)
SIBYLL 2.3 RC1 (2015)
$\nu_\mu + \bar{\nu}_\mu$
y > 0
2 < y < 4.5
4.5 < y < 6.5
y > 6.5
Conventional
y: full range
$E^3\phi$ [GeV^2 cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]



Prompt D^+ + c.c. for rapidity range $2.0 < y < 2.5$
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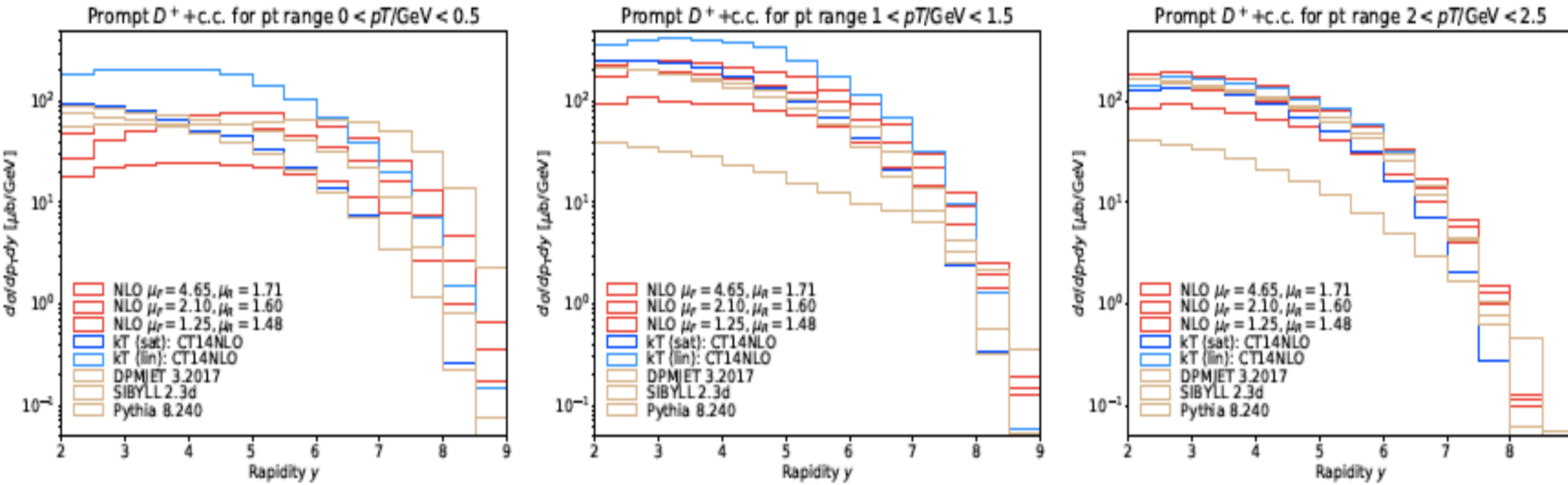
NLO $\mu_F = 2.10, \mu_R = 1.60$
NLO $\mu_F = 1.25, \mu_R = 1.48$
kT (sat): CT14NLO
kT (lin): CT14NLO
DPMJET 3.2017
SIBYLL 2.3d
Pythia 8.240
$d\sigma/dp_T dy$ [μb/GeV]
p_T [GeV]


Prompt D^++c.c. for pt range $0 < pT/\mathrm{GeV} < 0.5$
Prompt D^++c.c. for pt range $1 < pT/\mathrm{GeV} < 1.5$
Prompt D^++c.c. for pt range $2 < pT/\mathrm{GeV} < 2.5$
$d\sigma/dp_T dy$ [μb/GeV]
Rapidity y
NLO $\mu_F = 4.65, \mu_R = 1.71$
NLO $\mu_F = 2.10, \mu_R = 1.60$
NLO $\mu_F = 1.25, \mu_R = 1.48$
kT (sat): CT14NLO
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DPMJET 3.2017
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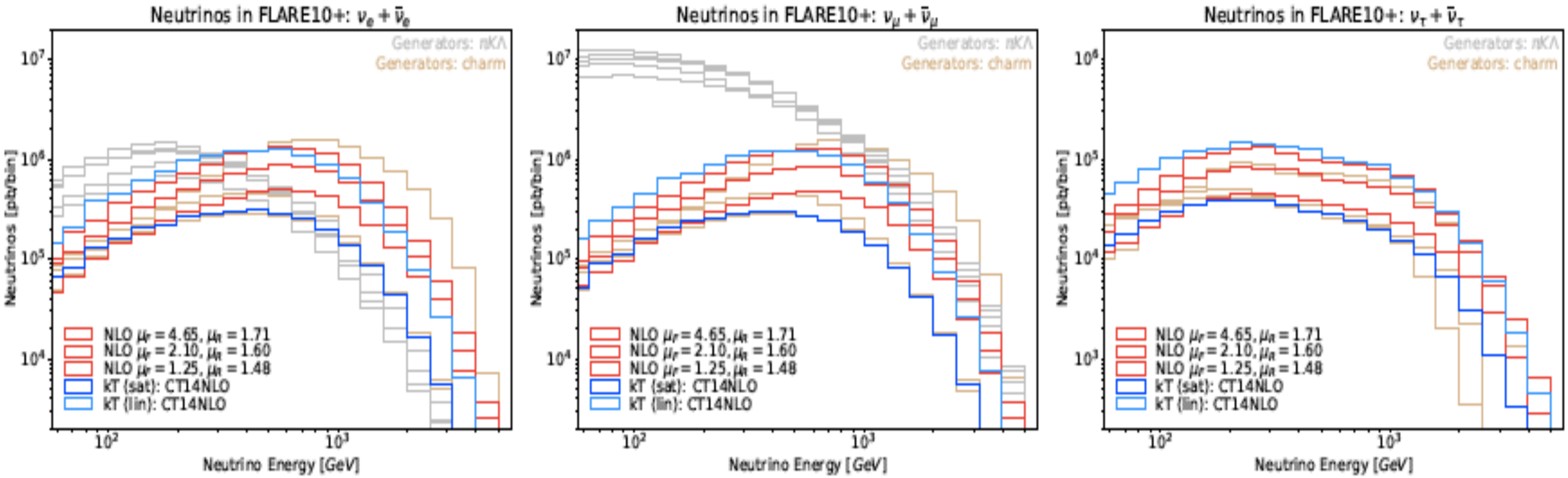
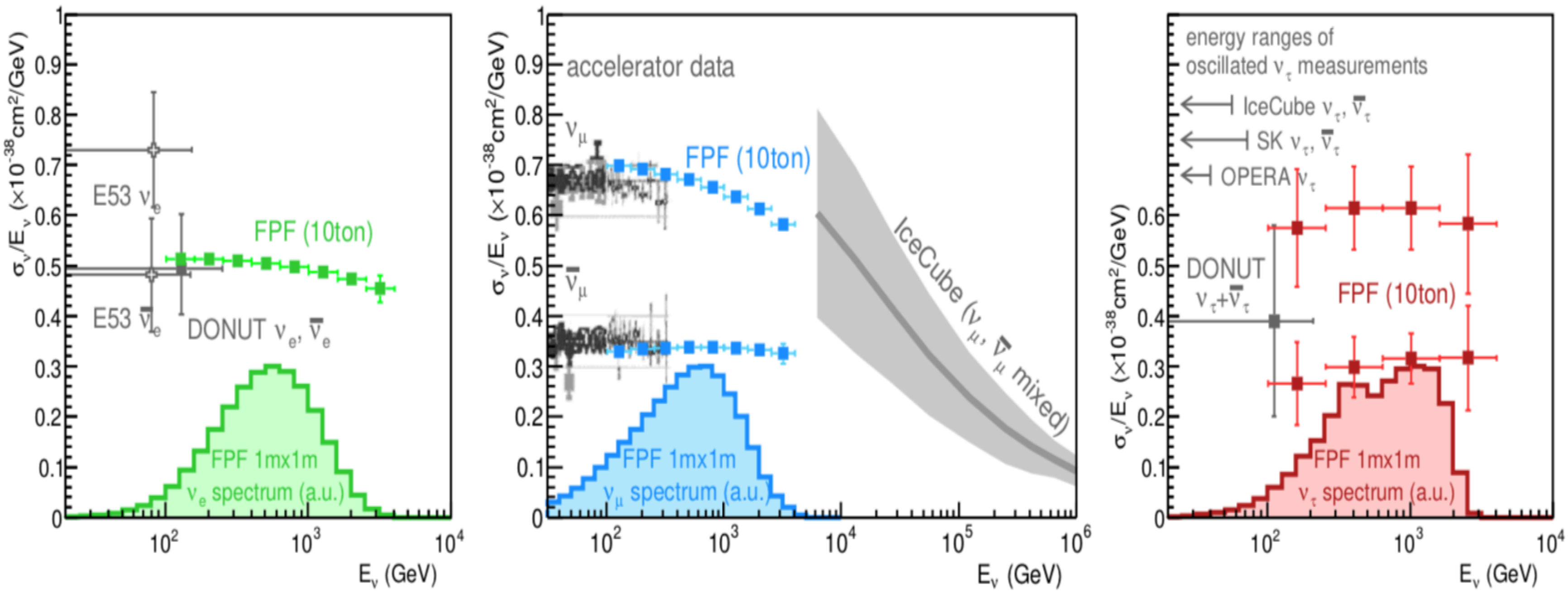
Pythia 8.240



Neutrinos in FLARE10+: $\nu_e + \bar{\nu}_e$
Generators: $\pi K \Lambda$
Generators: charm
Neutrinos [pb/bin]
Neutrino Energy [GeV]
NLO $\mu_F = 4.65$, $\mu_R = 1.71$
NLO $\mu_F = 2.10$, $\mu_R = 1.60$
NLO $\mu_F = 1.25$, $\mu_R = 1.48$
kT (sat): CT14NLO
kT (lin): CT14NLO
Neutrinos in FLARE10+: $\nu_\mu + \bar{\nu}_\mu$
Generators: $\pi K \Lambda$
Generators: charm
Neutrinos [pb/bin]
Neutrino Energy [GeV]
NLO $\mu_F = 4.65$, $\mu_R = 1.71$
NLO $\mu_F = 2.10$, $\mu_R = 1.60$
NLO $\mu_F = 1.25$, $\mu_R = 1.48$
kT (sat): CT14NLO
kT (lin): CT14NLO
Neutrinos in FLARE10+: $\nu_\tau + \bar{\nu}_\tau$
Generators: $\pi K \Lambda$
Generators: charm
Neutrinos [pb/bin]
Neutrino Energy [GeV]
NLO $\mu_F = 4.65$, $\mu_R = 1.71$
NLO $\mu_F = 2.10$, $\mu_R = 1.60$
NLO $\mu_F = 1.25$, $\mu_R = 1.48$
kT (sat): CT14NLO
kT (lin): CT14NLO

Neutrino cross sections



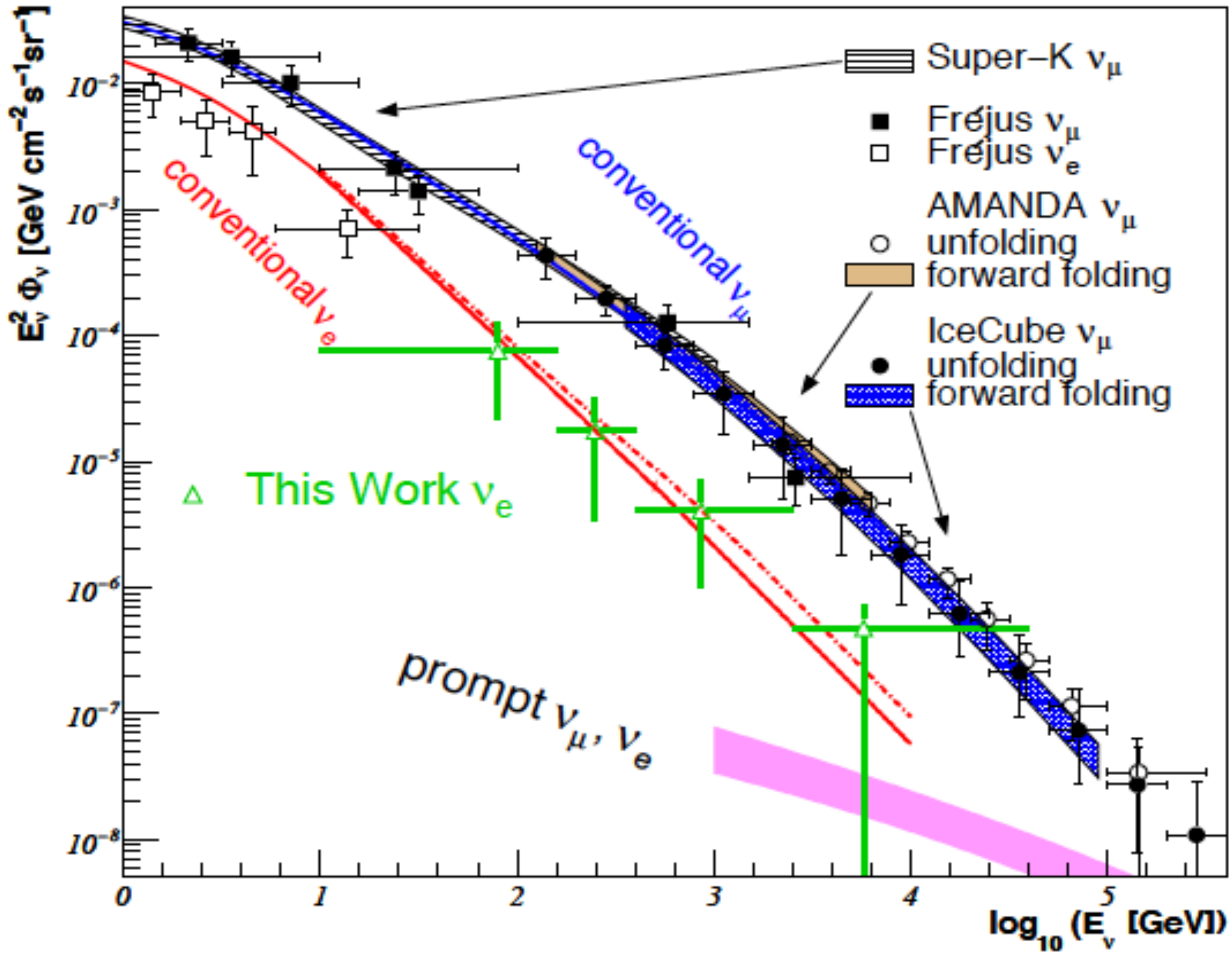
How does this constrained range of QCD parameters in hadronic charm production affect prompt atmospheric neutrino flux?

- Prompt neutrinos come from charmed meson decays, where charm mesons are produced in p-Air collisions

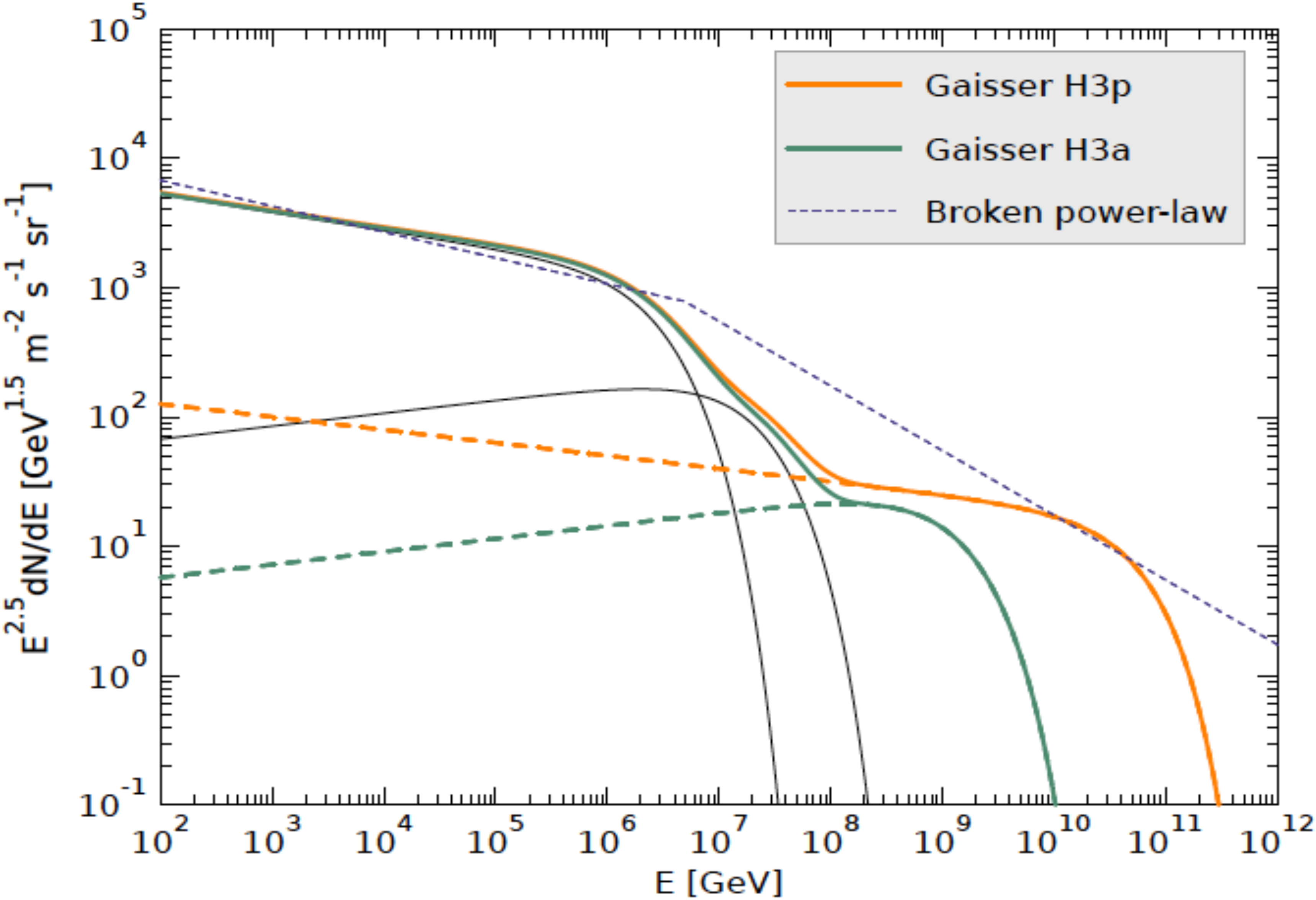
(i.e. p-air → charm → D-mesons)

IceCube has detected atmospheric neutrinos, and neutrino access in 10TeV to few PeV energy range (prompt neutrinos are the most important background). Detection of prompt neutrinos interesting in itself, probes pQCD

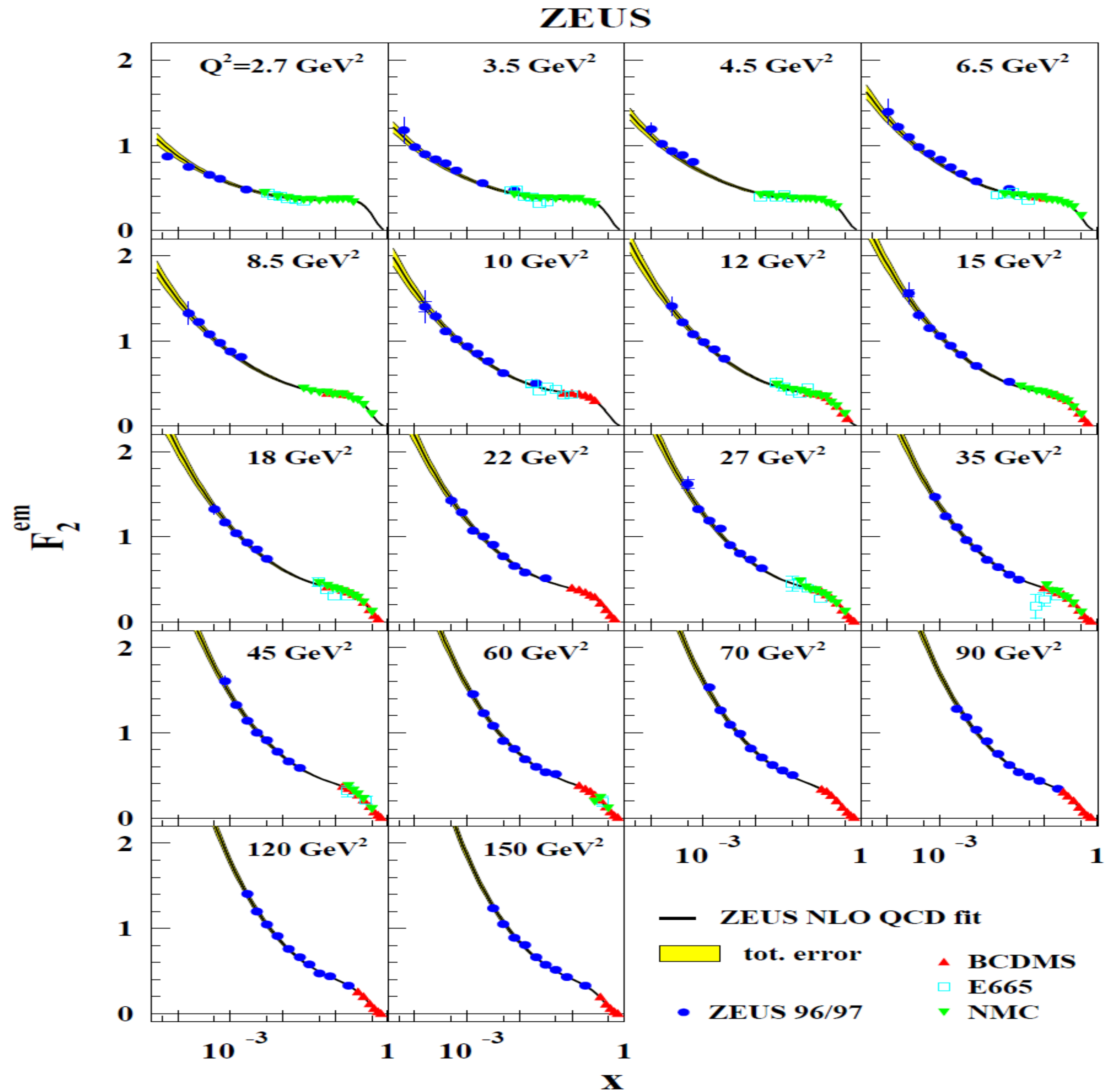
Atmospheric Neutrino Flux Measurements



Proton Flux

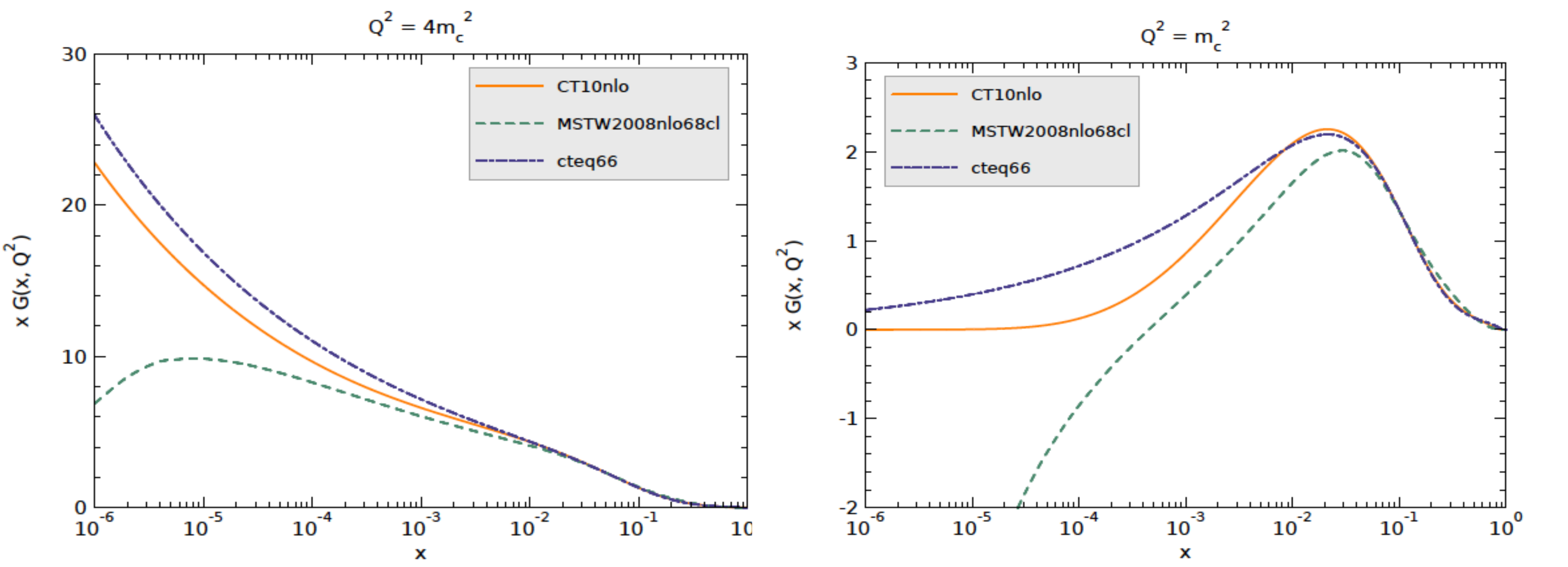


Gaisser H3p
Gaisser H3a
Broken power-law
$E^{2.5} dN/dE$ [$GeV^{1.5}$ m^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12}



F2 measured at HERA (ZEUS) as a function of Bjorken-x.

Gluon distributions at low Q^2 (updated PDFs: CT10, MRSTW and CTEQ66)

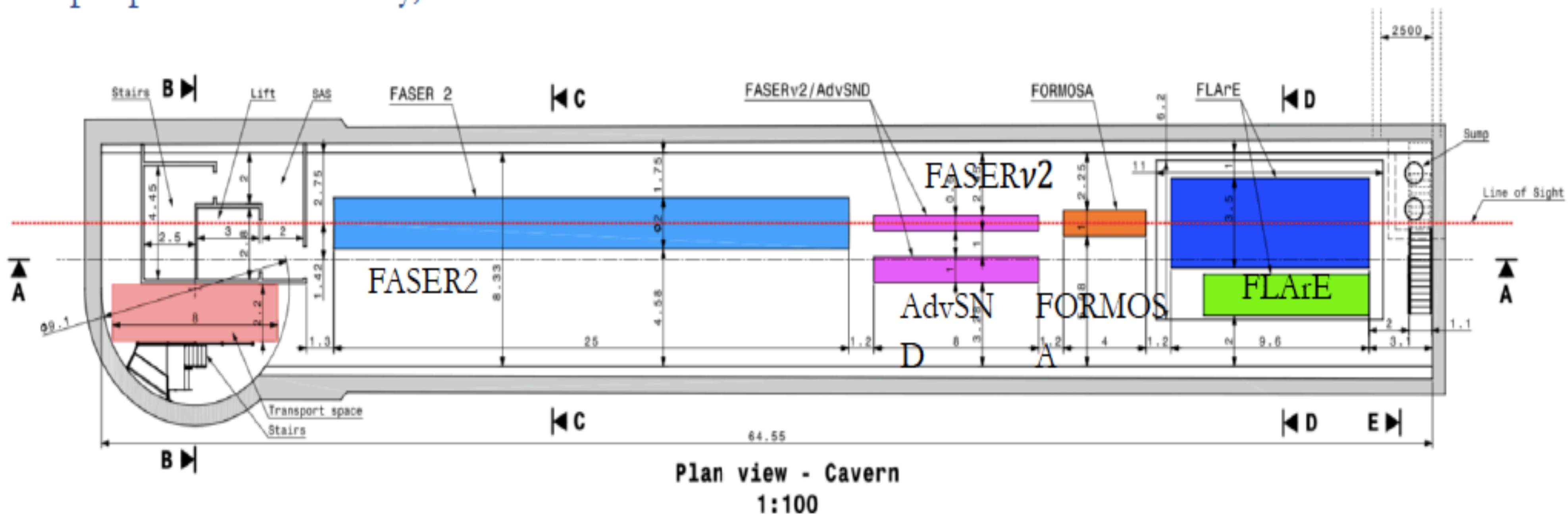


Proposed Experiments

- FLArE – *neutrinos*, LArTPC
- FORMOSA – Forward MicroCharge Search, BSM search, plastic scintillator

In a purpose-built facility, would like this:

- FASER2 – BSM search, magnetized spectrometer
- FASERν2 – *neutrinos*, emulsion-based
- AdvSND (and AdvSND2) – *neutrinos*, electronic, calorimeters



Short white paper 2109.10905

0.0 0.2 0.4 0.6 0.8 1.0